LBNL-6613E

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Integrating Energy and Indoor Environmental Quality Retrofits in Apartments

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November 2013

Funding was provided by the California Energy Commission, Public Interest Energy Research Program, Energy Related Environmental Research Program, through contract 500-09-022. Additional Support for this research was provided by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program of the U.S. Department of Energy under contract DE-AC02-05CH11231.

Acknowledgements

The authors thank Marla Mueller and Chris Early for Program Management; the Technical Advisory Committee for input and assistance in apartment recruitment, tenants and building owners and managers for their cooperation, Jim Fitzgerald and Terry Brennan for assistance in identifying retrofits and estimating their costs, and the Technical advisory committee plus Chris Stratton, Iain Walker, and Rick Diamond for reviewing drafts of the documents on which this final report is based.

ABSTRACT

Present home energy retrofit programs do not account for the effect of retrofits on indoor environmental quality conditions that influence comfort and health. This project developed a systematic procedure for selecting packages of retrofits that have the potential to simultaneously save energy and improve indoor environmental conditions in apartments. The procedure was used to select retrofits for 16 apartments and the resulting changes in indoor environmental conditions and apartment energy use were assessed. Implementation of the retrofits resulted in overall, but not universal, improvements in indoor environmental quality conditions. Ideally, the project would have provided unambiguous evidence of simultaneous energy savings. However, based on the large year-to-year changes in energy use in non-retrofit control apartments, the study was too small for accurate measurement of energy savings. Communication of study methods and results to utilities, policy makers, and owners and managers of subsidized multifamily housing has raised awareness of the opportunity to simultaneously save energy and improve comfort and indoor air quality when apartments are retrofit.

Keywords: apartment, energy, indoor environmental quality, protocol, retrofit

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EXECUTIVE SUMMARY

Introduction

The U.S. is implementing many energy retrofits in single-family homes and apartment buildings with the goal of reducing building energy consumption and carbon dioxide emissions, as well as improving national energy security. Existing protocols and tools to facilitate the selection and implementation of housing energy retrofit measures are typically based on energy models, engineering judgment and simplified cost-benefit analysis, rarely considering potential positive or negative effects of retrofits on indoor environmental quality (IEQ). Consequently, when retrofits are selected and implemented, the retrofits have the potential to degrade IEQ. However, if IEQ and building energy performance are considered in an integrated manner the retrofits may be able to simultaneously save energy and improve the IEQ conditions that affect people's comfort and health.

Project Purpose

The primary objectives of this project were to develop a systematic procedure for selecting packages of retrofits for apartments that simultaneously save energy and improve indoor IEQ conditions, and then to apply that procedure in a set of apartments and measure the resulting energy savings and IEQ improvements.

Project Methods

A unique protocol was developed for selecting packages of retrofits intended to simultaneously save energy and improve indoor IEQ conditions in apartments serving low-income California residents. Candidate retrofit measures were scored and ranked based on their estimated cost and predicted impacts on energy use, comfort, and indoor air quality (IAQ). The protocol was employed to select packages of retrofits for 16 total apartments from three apartment buildings in different cities in California. The selected retrofits were implemented by contractors certified by the Building Performance Institute. Diagnostic data, such as envelope leakage areas and ventilation equipment air flow rates were collected to inform the retrofit selection and subsequently to determine if selected retrofits met specifications. Energy savings were predicted with models. An extensive set of IEQ parameters were measured for two weeks before and two weeks after retrofit implementation, and the resulting measured data were compared to determine the effects of the retrofits on IEQ conditions. Also, monthly gas and electricity consumption data were collected for 12 months before the retrofits and for 12 months after the retrofits. Analogous energy data were collected from similar non-retrofit "control" apartments within the same apartment complexes. The changes in energy use in the retrofitted "study" apartments were compared to the changes in energy use in the control apartments.

Project Results

Pre-retrofit diagnostic measurements identified numerous retrofit opportunities. Bathroom and range hood fans typically had much lower air flow rates than required in standards and were noisy. Pilot lights, present in some gas stoves were a source of energy waste and indoor pollutants. Attics often had minimal insulation. Single pane and leaky windows and sliding glass doors, leaky envelopes, and leaky ducts were present in some apartments. Heating and cooling systems were sometimes old and inefficient and some natural-draft water heaters posed risks of combustion-pollutant backdrafting. The selected retrofits addressed these and other deficiencies and included a set of a-priori retrofits to provide ventilation consistent with current standards. Average spending on retrofits per apartment was $12,700, $7700, and $9000 for apartments in Buildings 1 – 3, respectively.

The measurements indicate an overall improvement in IEQ conditions after the retrofits. Comfort conditions, bathroom humidity, and concentrations of carbon dioxide, acetaldehyde, volatile organic compounds, and particles generally improved. Formaldehyde and nitrogen dioxide levels decreased by approximately 50% in the building with the highest concentrations, were effectively unchanged in a second building, and increased substantially in a third building where concentrations were low. IEQ parameters other than particles improved more in apartments with the installation of continuous mechanical ventilation systems. In general, larger percent increases in air exchange rates were associated with larger percent decreases in indoor levels of the pollutants that primarily come from indoor sources.

Pre-retrofit modeling indicated annual energy savings of 21%, 17%, and 27% for the study apartments in buildings B1-B3, respectively. Based on a comparison of changes in energy use of study apartments to energy use changes of control apartments, total measured savings of gas energy plus site electrical energy were 28% in B1, 5% in B2, and 3% in B3. Given the small number of study apartments and the very substantial year-to-year changes in energy use within control apartments, the project yielded no conclusive evidence of energy savings. Apartment energy use increased with number of occupants and with floor area; however, the association with occupancy was most evident. Climate differences did not appear to be the major driver for the variability in energy use among apartments. Changes in occupant behaviors affecting energy use may have overwhelmed and obscured the energy savings in this small study. Much larger prior studies employing similar retrofits indicate that the retrofits usually do save energy. Surveys indicated that occupants were generally very satisfied with the retrofits.

Project Benefits

The project resulted in a new protocol for selecting retrofits in apartments, it identified opportunities for retrofits that simultaneously save energy and improve IEQ, and it showed that implementation of these retrofits resulted in overall improvements in IEQ. Ideally, the project would have also provided unambiguous evidence of simultaneous energy savings. However, based on the large year-to-year changes in energy use in non-retrofit control apartments, the study was too small for accurate measurement of energy savings. Communication of study methods and results to utilities, policy makers, and owners and managers of subsidized multifamily housing has raised awareness of the opportunity to simultaneously save energy and improve comfort and indoor air quality when apartments are retrofit.

CHAPTER 1: INTRODUCTION

Approximately 20 percent of all U.S. households live in multifamily buildings (U.S. Census Bureau 2010). Older apartments serving low-income populations are often poorly maintained, with deficiencies in energy performance and in indoor environmental quality (IEQ) such as poorly controlled thermal comfort conditions and high levels of pollutants (Jacobs, Kelly et al. 2007, Northridge, Ramirez et al. 2010). The U.S. is implementing many energy retrofits in homes with the goal of reducing building energy consumption and carbon dioxide emissions, as well as improving national energy security. Several practical protocols and tools exist to help with the selection and implementation of housing energy retrofit measures (Noris, Delp et al. 2013). These protocols are typically based on energy models, engineering judgment and cost-benefit analysis. Features of IEQ that may be affected by retrofits include thermal comfort conditions, indoor air pollutant concentrations, and acoustic and lighting conditions (Mudarri 2006, Fisk 2009, Institute of Medicine 2011). Although retrofit efforts provide an opportunity to simultaneously save energy and improve occupant's health and comfort, potential IEQ improvement opportunities are rarely considered during selection of retrofits measures. If IEQ is neglected when retrofits are selected and implemented, the retrofits have the potential to degrade IEQ. In particular, sealing leaks in building envelopes, a very common practice, will reduce outdoor air ventilation and lead to increases in indoor air concentrations of indoor-generated air pollutants.

Improvements of IEQ have been demonstrated in a few home retrofit studies. Studies from New Zealand reported improved comfort, indoor air quality (IAQ), and health symptoms resulting from upgrading insulation and replacing ineffective heating systems or heating systems that vent combustion gases to indoors (Howden-Chapman, Matheson et al. 2007, Howden-Chapman, Pierse et al. 2008). Because pre-retrofit indoor air temperatures were lower than typical temperatures in U.S. homes and because many of the New Zealand homes had heating systems that vented combustion gases indoors, the results of that study are not generally applicable to U.S. homes. Some retrofit studies have focused on a specific IAQ challenge in multifamily buildings -- the inter-apartment transport of pollutants. Bohac, Hewett et al. (2010) reported reduced transfer of secondhand tobacco smoke between apartments resulting from apartment air sealing and increased ventilation. However, to the best of our knowledge, no prior study has empirically investigated the potential for simultaneous energy and IEQ benefits when broad packages of retrofits are implemented in apartments.

The primary objectives of this project were to develop a systematic procedure for selecting packages of retrofits for apartments that simultaneously save energy and improve indoor IEQ conditions, and then to apply that protocol and measure the resulting energy savings and IEQ improvements.

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CHAPTER 2: Methods

2.1 Overview of methods

A unique protocol was developed for selecting packages of retrofits intended to simultaneously save energy and improve indoor environmental quality (IEQ) conditions in apartments serving low-income California residents. The protocol was employed to select packages of retrofits for 16 total apartments from three apartment buildings in California. The selected retrofits were implemented by contractors certified by the Building Performance Institute. Diagnostic data, such as envelope leakage areas and ventilation equipment air flow rates were collected to inform retrofit selection and subsequently to determine if selected retrofits met specifications. An extensive set of IEQ parameters were measured for two weeks before and two weeks after the retrofits were implemented. The resulting measurement data were compared to determine the effects of retrofits in IEQ conditions. Energy savings was modeled. Also, monthly gas and electricity consumption data were collected for 12 months before the retrofits and for 12 months after the retrofits. Analogous energy data were collected from a set of similar non-retrofit "control" apartments. The changes in energy use in the retrofitted "study" apartments were compared to the changes in energy use in the control apartments.

2.2 Retrofits

2.2.1 Retrofit selection protocol

A point-based protocol was developed to account for retrofit costs and the expected impacts of retrofits on energy use, indoor air quality (IAQ), and comfort. Point assignments for specific retrofits, drawn from a list of candidate retrofits, were based on modeled energy savings, predicted changes in indoor air pollutant concentrations, and some professional judgments in the comfort category informed by a review of applicable literature and calculations. Data obtained from apartment inspections and diagnostic measurements were used in the calculation of points. The sum of points assigned to each retrofit measure was divided by the estimated retrofit cost, yielding a cost-normalized benefit score. Retrofit measures were then ranked by their cost-normalized benefit scores.

In addition to the ranked retrofit measures, a set of a-priori retrofits was adopted for implementation whenever possible. The a-priori retrofits include measures selected to comply with elements of the ASHRAE residential ventilation standard (ASHRAE 2010) which is the basis for the associated California standard, measures to prevent combustion appliance safety hazards, and a few low-cost measures with benefits expected to nearly always exceed costs. These measures are described subsequently and the rationale for selecting them as a-prior measures is provided.

A retrofit budget was assigned for each apartment building. The a-priori measures were selected for implementation whenever applicable and acceptable to the building owner and tenants. The remaining retrofit budget was allocated to the ranked retrofit measures until the allotted budget was expended. To treat tenants equitably, the expenditure per apartment was maintained within a building within a small range.

The following were selected as a-priori retrofit measures:

- Upgrading or adding bathroom and kitchen ventilation to meet the requirements of the ASHRAE residential ventilation standard (ASHRAE 2010).
- Provision of mechanical ventilation at 150% of the rate prescribed in this standard. A higher than prescribed rate was selected because air infiltration may come from surrounding apartments. Also, when exhaust ventilation is employed some of the air drawn into the apartment by the exhaust fan will come from surrounding apartments.
- Air sealing of the sections of the apartment envelope that connect to other apartments or to common areas of the apartment building, to reduce the inter-apartment tobacco smoke and odor transport that drive many complaints.
- Air sealing of the sections of the apartment envelope that connect to outdoors when mechanical ventilation is provided is an a-priori measure, because the cost is moderate and envelope sealing should save energy.
- Isolation of the appliance from the occupied space or replacement by a forced-combustion appliance when a combustion safety test and calculations, accounting for the expected post-retrofit flow rates of kitchen and bathroom exhaust fans, indicated a backdrafting risk for natural draft combustion appliances.
- Installing a high-efficiency filter in the forced-air heating system and reducing air bypass around the filter, installing a low-flow showerhead (unless already present), adding insulation to the hot water tank and pipes, and replacing incandescent light bulbs with compact fluorescent bulbs because of their low cost and anticipated larger benefits.
- In addition, the a-priori measures included tenant education about improving indoor air quality (IAQ), energy efficiency and comfort in their apartment, as well as education related to the appropriate use of the implemented physical retrofits. The education used the Department of Housing and Urban Development (HUD) Healthy Homes booklet, available at http://www.hud.gov/offices/lead/library/hhi/HYHH_Booklet.pdf, and documents developed as part of the current project (see Appendix 1). The education was implemented during a home-visit by a researcher. Written documents were provided and reviewed verbally and questions from tenants were answered. Protocols were reviewed and approved by Lawrence Berkeley National Laboratory's institutional review board and tenants provided informed consent.

Scored and ranked retrofit measures were selected from a list of candidate retrofit measures developed based on discussions with experts in the fields of building energy efficiency and IEQ (including both researchers and practitioners), prior literature, and retrofit guidelines describing how retrofits affect energy consumption and IEQ. Sample calculations of expected energy savings and IEQ changes facilitated the development of the list. Retrofits included in the list include the following: replacement of heating and cooling systems; duct sealing; addition of thermal insulation to walls and attics; replacing windows or sliding glass doors; replacement of refrigerators, gas stoves with pilot lights, and water heaters; and installation of energy efficient wall-mounted particle filtration systems.

The point-based system for ranking of retrofits assigned points on a -3 through +3 scale in three impact categories: energy; IAQ; and comfort.

- In the energy category, a score of +1 was assigned for a projected apartment annual energy savings less than $50, +2 for $50 to $100 annual savings, and +3 for greater than $100 annual savings. If a retrofit increased energy use, negative energy points were assigned. To estimate how the retrofits affect apartment energy consumption, the Home Energy Saver Pro (HES) [http://hespro.lbl.gov/pro/] tool was employed. This web-based retrofit selection tool was developed for single-family homes and townhouses. The tool considers the initial condition of a residence, applies a building energy model, and suggests energy retrofits with their associated yearly energy savings and retrofit costs. For application to apartments, the townhouse option was used, as it was the best tool for our application available in HES. A high level of attic insulation (R-60) was specified in HES if there was another apartment located above. About half of apartments in the study were equivalent to townhomes with independent entrances from the street and no dwelling above or below. All apartments had independent heating, and space cooling systems when present were also independent.

- In the IAQ category, positive points were allocated based on the projected reductions in indoor air concentrations of nitrogen dioxide (NO_2), and particles less than 2.5 μm in diameter (PM2.5). The category boundaries for IAQ scoring were based on 10% of the outdoor air pollution standard for that pollutant [19]. Thus, for example, for NO_2 with an outdoor air standard of 56 $\mu g/m^3$, scores were +1 for a reduction in indoor concentration less than 5.6 $\mu g/m^3$, +2 for reductions of 5.6 to 11.2 $\mu g/m^3$, and +3 for indoor concentration reductions greater than 11.2 $\mu g/m^3$. Negative IAQ scores would have been assigned for projected increases in NO_2 or PM2.5 concentrations; however, we did not encounter such cases. If a retrofit was projected to affect both NO_2 and PM2.5 concentrations, scores for each of the affected IAQ parameters were summed but the total category score was constrained within the -3 to +3 range. The changes in indoor pollutant concentrations were calculated using a mass balance model. These calculations used indoor pollutant emission rates published in the literature.

- Comfort scores, considering effects of retrofits on noise and thermal comfort, were based on reported benefits in the literature for the various retrofits supplemented by calculations, but necessarily relied on engineering judgment due to the scarcity of quantitative data. Noise and thermal comfort points were assigned for replacement of noisy kitchen and bathroom fans with quieter fans, provision of portable fans that help keep people comfortable during warm weather in apartments with no air conditioning, and improvement of wall insulation or windows which are associated with reduced drafts and radiant discomfort when it is cold outdoors.

The sum total score for each retrofit, constrained between -9 and +9, was initially divided by a preliminary estimate of retrofit's cost available from the HES tool and from a table of costs obtained through consultation with several individuals with extensive retrofit experience. For the final stages of retrofit selection, apartment-specific costs provided by the retrofit contractor were utilized.

The retrofit selection protocol is described in greater detail in Appendix A2. The appendix describes the methods used to collect data on buildings and apartment conditions, provides data collection forms, provides instructions for the energy and indoor air quality calculations, and shows in detail how points are calculated and retrofits are ranked. While calculations of scores specific to a retrofit project are strongly preferred, to simplify protocol use, Table 1 shows the indoor air quality and comfort points determined for the current project. These point assignments in the indoor air quality and comfort categories can be used as defaults for similar apartments in California. No default points are provided in the energy category since the HES Program is readily available for estimation of energy savings.

As an example of the process, replacement of the gas range with pilot light with a pilotless range received a +3 total score. The energy score was +1 based on an annual energy cost savings of $38. The IAQ score was +2, with +1 based on an indoor NO_2 reduction of 3 $\mu g/m^3$ plus another +1 based on an indoor PM2.5 reduction of 0.2 $\mu g/m^3$. Dividing the +3 benefit score by the installed cost of $680, resulted in a normalized score of 4.4/$1,000. In another example, addition of a wall mounted particle air cleaner received a -1 energy score based on the projected annual electricity cost of $18 (assuming half time operation) and a +3 IAQ score based on a projected decrease in PM2.5 greater than 11.2 $\mu g/m^3$. With the installed cost of $813, the cost-normalized benefit score was 2.5/$1,000.

Table 1: Benefit scores in the IAQ and comfort categories for the current project and form for calculating total cost normalized benefit scores

Retrofit		Score				Cost ($)[B]	Score/$
		IAQ	Energy [A]	Comfort	Total		
Install cover on window air conditioners			+1		1		
Add external wall insulation			HES	+1	HES+1		
Add ceiling insulation in top-floor apartments			HES	+1	HES+1		
Install programmable thermostat			HES		HES		
Replace air conditioner because	Inefficient		HES		HES		
	Noisy			+1	1		
	Water leak	+3			3		
Repair air conditioner because	Inefficient		HES		HES		
	Noisy			+1	1		
	Water leak	+3			3		
Replace heating device because	Inefficient		HES		HES		
	Noisy			+1	1		
	Polluting	+3			3		
Repair heating device because	Inefficient		HES		HES		
	Noisy			+1	1		
	Polluting	+3			3		
Replace unvented heating device with a vented one (ensure adequate venting for all combustion appliances)		+1	HES		HES+1		
Seal and insulate HVAC ducts in unconditioned space and cavities			HES		HES		
Add air-moving device (fan)	With AC		+1		1		
	Without AC			+1/2/3[C]	+1/2/3		
Replace broken windows			+2/3[D]	+1	3/4		
Upgrade existing windows			HES	+1	HES+1		
Fix leaking water pipes causing water damage		+3			3		
Water seal in bath		+1			1		
Limited scale moisture and mold retrofits (budget < $2K)		+3			3		
Replace pilot ignition combustion appliances (gas stove, furnace) with comparable or more efficient units with electronic ignition		+1	HES		HES+1		
Replace combustion appliance (furnace, water heater) with potential back drafting with a forced combustion appliance		+1	HES		HES+1		
Replace combustion appliance (furnace, water heater) with faulty vent		+1	HES		HES+1		
Replace inefficient water heater with a more efficient one			HES		HES		
Install CO monitor		+1			1		
Energy efficient lighting upgrade (i.e., CFLs)			HES		HES		
Vent outside existing dryer		+2/3[E]			2/3		
Replace inefficient refrigerator			HES		HES		

[A] The label HES indicates that the energy score was based on the yearly savings from HES web-based tool using the criteria outlined on Table A2.5.

[B] Obtained from Table A2.3

[C] A +1 score increment was assigned for each of the following conditions: cooling degree days >560 ^{o}C-day; apartment on top floor; apartment with south exposure.

[D] Assign +2 or +3 based on window conditions and apartment location.

[E] Assigned a +2 for an electric dryer and a +3 for a gas dryer.

2.2.2 Apartment recruitment

To be considered for inclusion in this study, apartment buildings needed to be located in California's coastal or central-valley regions, serve low income tenants, have four or fewer floors, have been constructed prior to 1990 with no subsequent major energy retrofits, have at least 15 apartments, and have no heating, cooling, or ventilation systems serving multiple apartments. Owners and managers of candidate buildings were contacted to determine if these criteria were met and to assess their interest in participating in the study. Three apartment buildings were selected. These buildings, denoted B1, B2, and B3, are located in Sacramento, Richmond, and Fresno, respectively. Sacramento and Fresno are located in central California where both winter heating and summer air conditioning are normally required. Richmond is located in the San Francisco Bay area, near the Bay, where air conditioning is generally not employed. These properties provided subsidized housing, buildings were low-rise, and were older than 20 years. Each apartment had meters for electricity and gas, an independent heating system and, if present, an independent air conditioning system. Study costs limited the number of apartments that could be retrofit and evaluated. Study protocols were approved by the Lawrence Berkeley National Laboratory's Institutional Review Board.

Flyers were used to recruit 16 study apartments that were subsequently retrofit, and to recruit similar control apartments that are not retrofit. Approximately 12 apartments in each property were recruited for the initial inspection with diagnostic measurements. Via implementation of the retrofit selection protocol, retrofit package recommendations were developed for each inspected apartment. Apartments with greater improvement opportunities and with cooperative occupants were given priority. In case of equal improvement opportunities, study apartments were selected randomly. Only apartments whose residents reported that no smoking was allowed inside the unit were included in the project.

2.2.3 Retrofit implementation

The retrofit recommendations were discussed with building owners and tenants and, in nearly all cases, the suggested retrofit measures were acceptable to both tenants and owners. The retrofits were implemented by contractors certified by the Building Performance Institute. In each of the three properties, five or six apartments were retrofit with target budgets of $8000 to $10,000 per apartment. The retrofits of apartments in B1 took place between August 1 and August 29, 2011. For B2 and B3 the retrofit periods were January 3 – February 1, 2012 and March 5 – March 29, 2012.

2.2.4 Pre- and post-retrofit diagnostic measurements

To collect data to input into the retrofit selection protocol, buildings and apartments were characterized via building manager interviews, inspections using checklists, and diagnostic measurements. The parameters determined via diagnostic measurements included the following: air flow rates for bathroom and kitchen exhaust fans; envelope air leakage; ventilation system duct leakage; and the results of a combustion appliance zone (CAZ) worst-case depressurization test. Bathroom exhaust fan airflow rates were measured with a rotating vane anemometer within an integrated flow hood (TESTO 417, Testo Inc, Sparta NJ) or a powered flow hood. The powered flow hood uses a calibrated fan (Minneapolis Duct Blaster fan and a DG700 pressure control from Energy Conservatory, Minneapolis), with zero pressure drop maintained across the hood so that flow rates are unaffected by the measurement system (Wray, Walker et al. 2002). Kitchen range hood airflows were also measured with the powered flow hood. Envelope air leakage was measured using a blower door test according to ASTM E779-10 (ASTM 2010). To measure duct leakage, the delta Q test method was employed according to ASTM E1554-07 (ASTM 2007). The test provides supply and return duct leakage based on a blower door test while operating and not operating the heating, ventilating, and air conditioning (HVAC) system. The data obtained when the HVAC system was off was used to determine envelope leakage. Blower door tests utilized a Minneapolis Blower Door and the DG700 pressure control from the Energy Conservatory (Minneapolis, MN). In apartments with combustion appliances inside the apartment, the combustion appliance zone (CAZ) worst-case depressurization test was performed (Building Performance Institute 2012). Additionally, the likelihood of failing the CAZ worst-case depressurization test after retrofitting bathroom fans and range hoods was estimated using the results of the blower door test to model apartment depressurization as a function of exhaust air flow rate. The diagnostic measurements described above were repeated after retrofits were implemented.

2.3 Evaluation of effects of retrofits on IEQ conditions

2.3.1 Basic strategy

Indoor and outdoor air pollutant concentrations and indoor temperature and humidity were measured for two weeks prior to retrofit implementation and for two weeks after retrofit implementation. The pre-retrofit measurements, retrofits, and post-retrofit measurements occurred during the same season. The results of measurements made after retrofits were compared to the results of measurements made prior to the retrofits.

2.3.2 IEQ parameters and measurement methods

The IEQ parameters selected for measurement at indoor and outdoor locations include the following: temperature (T); relative humidity (RH); and concentrations of carbon dioxide (CO_2), carbon monoxide (CO), particles less than 2.5 micrometers in diameter (PM2.5), nitrogen dioxide (NO_2), acetaldehyde, formaldehyde, and a suite of volatile organic compounds (VOCs). The measurements were conducted using time-resolved and time-integrated methods. The parameters monitored with time-resolved instruments included carbon dioxide (CO_2) and carbon monoxide (CO) measured using Langan Model L76v (Langan Products, Inc., San Francisco, CA, USA). This instrument incorporates a GE Telaire 7001 (GE Measurement & Control Solutions, Billerica, MA, USA) for CO_2 quantification, while the CO was assessed with a built in electrochemical passive sensor (Langan Model T15n). TSI Dust Trak instruments (TSI Inc., Shoreview, MN, USA) were used to measure PM2.5. Temperature and RH were measured with Onset HOBO U12 sensors (Onset Corp., Bourne, MA, USA), while to monitor RH in bathrooms with showers the Onset HOBO U23 sensors were employed. These sensors are capable of withstanding the greater humidity levels encountered in bathrooms. Time-integrated sampling methods were employed to measure nitrogen dioxide (NO_2), formaldehyde, acetaldehyde, and volatile organic compounds (VOCs). These methods employ diffusive sample collection (no pumping required) and subsequent analysis of the samples in the laboratory. NO_2 was collected using Ogawa samplers and sampling media (Ogawa & Co. USA, Inc., Pompano Beach, FL, USA), and quantified through ion chromatography (IC). A validation of the NO_2 measurement methods is provided by (Singer, Hodgson et al. 2004). Formaldehyde and acetaldehyde were sampled using Waters cartridges (Waters Corporation, Milford, MA, USA) containing 2,4-dinitrophenylhydrazine (DNPH) coated with silica and then quantified by high-performance liquid chromatography (HPLC). Side by side active and passive sampling with these cartridges have been reported in two studies (Shinohara, Kumagai et al. 2004) and (Mullen, Li et al. 2013). When calculating aldehyde concentrations, the more recent, and lower passive sampling rates of validation experiments (Mullen, Li et al. 2013) were applied because the sampling duration, concentration range, and environments were better matched to the conditions of this study. Volatile organic compounds were passively sampled using an adsorbent (stainless steel tube filled with Tenax®-TA, Supelco P/N 28271-U), subsequently thermally desorbed for analysis by gas chromatography-mass spectroscopy (GC-MS) The VOC methods are described in (Wu, Apte et al. 2011). A set of approximately 30 VOCs was quantified. The overall apartment ventilation flow rate over each monitoring period was assessed using the perfluorocarbon tracer (PFT) method. To measure this time-integrated parameter, two to three continuous passive emitters of hexafluorobenzene were installed in each apartment. This tracer was then sampled and analyzed using the passive Tenax tubes and GC-MS methodology employed for VOCs (Batterman, Jia et al. 2006). Hexafluorobenzene sources were placed in different locations within the apartments away from operable windows and doors. The measured apartment ventilation rate represents the total airflow through the apartment, without distinguishing between the airflow coming from outdoors or from other parts of the building.

All the instruments and samplers for the IEQ measurements were placed in a protective enclosure and located in a central location inside the apartment (away from windows and doors) about 2 m above the floor. The indoor Tenax tubes were located outside the indoor enclosure to avoid possible contamination caused by pollutants emitted by the enclosure. Temperature and RH were also measured in any bathroom with a shower and in the main bedroom. Additional NO_2 passive samplers were located in the main bedrooms of each apartment. The outdoor instrumentation was placed at approximately 1.5 m of height inside a locker located in a central location within the apartment complex.

A summary of the methodologies employed for the IEQ measurements is presented in Table 1. The CO and CO_2 instruments were calibrated with gas standards before and after measurements in each building. The PM2.5 instruments were initially checked by comparison of their output to PM mass determined from the weight changes and air flow rates through filters (Chan and Noris 2011), and were subsequently inter-compared before and after measurements in each building. To minimize device-induced variability in the measurements, the same real time instruments for CO, CO_2, PM2.5, temperature, and relative humidity were utilized for the pre- and post-retrofit measurements of each apartment. Consequently, the uncertainties in changes in these parameters between the pre- and post-retrofit measurement periods will be less than the uncertainties indicated in Table 1. For the passive methods, field blank and duplicates tubes were analyzed. Laboratory blanks and field blanks were used for quality control, while duplicates were utilized to determine relative precision. Calibration checks and calibration standards were also performed for each set of field samples to assure performance of the laboratory instruments and techniques.

Table 2: Description of parameters, locations, techniques and instruments used for indoor and outdoor measurements

Parameter	Locations	Resolution	Sampler	Instrument	Uncertainty Estimate	Uncertainty Sources
Temperature (T) and Relative Humidity (RH)	Indoor & outdoor enclosures, bedroom, bathroom	Time resolved	-	Onset HOBO U12 or U23 in bathroom	±0.35 °C ±3.5%	Product Literature
Carbon dioxide (CO_2)	Indoor & outdoor enclosures	Time resolved	-	Langan Model L76v – GE Telaire Model 7100	90 ppm (7%) at 1260 ppm average concentration	Repeated instrument calibrations
Carbon monoxide (CO)	Indoor & outdoor enclosures	Time resolved	-	Langan Model L76v – Model T15n	0.7 ppm at 2 ppm average concentration	Repeated instrument calibrations
Particle matter (PM) mass	Indoor & outdoor enclosures	Time resolved	-	TSI Dust Trak	0.8 μg/m^3 precision	(Chan and Noris 2011)
Nitrogen dioxide (NO_2)	Indoor & outdoor enclosures, main bedroom	Time integrated	Ogawa badge	Ion Chromatography	~8%	(Singer, Hodgson et al. 2004)
Acetaldehyde Formaldehyde	Indoor & outdoor enclosures	Time integrated	Waters DNPH tube	High Performance Liquid Chromatography	Less than 1.2 μg/m^3 or 10% Less than 1.8 μg/m^3 or 12%	Analysis of replicates
Volatile organic compounds (VOCs)	Outdoors, living room, main bedroom	Time integrated	Tenax tube	Gas Chromatography Mass Spectrometry	10% coefficient of variation of replicate measurements	(Wu, Apte et al. 2011)
Ventilation rate (VR)	Living room, main bedroom	Time integrated	Tenax tube	Gas Chromatography Mass Spectrometry	20%[a]	Analysis of replicates

[a]accounts for uncertainty in measurement of tracer gas concentration based on replicate data, does not account for errors due to imperfect mixing of tracer in indoor

At least one resident on each of the study apartments participated in the occupant surveys. They were composed of three sections: baseline, pre-retrofit and post-retrofit. The surveys included questions about apartment conditions, occupant behaviors, and satisfaction with air quality and the implemented retrofits. The surveys and other study protocols were approved by the Lawrence Berkeley National Laboratory's Institutional Review Board.

2.3.3 Analysis of IEQ data

To indicate how the retrofits affected thermal comfort conditions, for each apartment the percent of time with the indoor air temperatures at the central measurement location exceeding or falling below the applicable ASHRAE Thermal Comfort zones (ASHRAE 2009) were calculated for pre-retrofit and post-retrofit periods. For B1, retrofit in summer, the percent of time with an indoor air temperature above 27.4 ^{o}C was calculated. For apartments in B2 and B3, retrofit in winter, the percent of time with indoor air temperatures below 20.5 ^{o}C was calculated. The boundaries of ASHRAE's thermal comfort zone vary somewhat with humidity and values of 27.4 ^{o}C and 20.5 ^{o}C were based on typical indoor values of humidity. Also, the thermal comfort boundaries only apply when air speeds are less than 0.2 m s^{-1}.

Also calculated were the percent time with overcooling in B1 (studied in summer) and overheating in B2 and B3 (studied in winter) relative to ASHRAE's summer and winter thermal comfort zones. It is not clear if the resulting data indicate the extent of thermal discomfort or if the data indicate tenant willingness to pay for energy to be a slightly cooler in summer and warmer in winter.

The measured values of apartment relative humidity (RH) were almost always between 35% and 55%, never indicating a humidity problem. There were periods of elevated RH in the main bathroom, potentially contributing to mold growth, thus, the percent time with bathroom RH greater than 75% was used as a metric of performance.

For carbon dioxide, formaldehyde and acetaldehyde the average pre-retrofit and post- retrofit indoor and outdoor concentrations were calculated, and then the indoor minus outdoor differences were calculated. These calculations are based on two weeks of data before and after the retrofits. To characterize the effects of the retrofits, percent improvements in these average concentration differences were then calculated.

In many cases, large changes in outdoor air concentrations of NO_2 and PM2.5 made changes in the indoor, or indoor minus outdoor, concentration differences of NO_2 and PM2.5 invalid as indicators of the effect of the retrofits on indoor air quality. Consequently, adjusted pre-retrofit indoor air concentrations of NO_2 and PM2.5 were calculated. The adjustments, based on mass balance models, yielded estimates of what the pre-retrofit indoor air concentrations would have been if the outdoor air concentration during the pre-retrofit period had been the same as the post-retrofit outdoor air concentration.

For NO_2, a change in outdoor air concentration of ΔC_0 will change the indoor air NO_2 concentration ΔC_i by less than ΔC_0 because of indoor NO_2 depositional losses. From a steady state mass balance

$$\Delta C_i = \Delta C_o \, \lambda_v / (\lambda_v + K_d) \qquad (1)$$

where λ_v is the air exchange rate (h^{-1}) and K_d is the NO_2 deposition loss constant (h^{-1}). This equation assumes negligible NO_2 depositional losses as NO_2 laden outdoor air enters the building. Nazaroff, Gadgil et al. (1993) provide data from a review of literature that indicates values of K_d from 0.2 to 1.2 h^{-1}. Yang, Lee et al. (2004) assumed that K_d = 1.0 h^{-1} based on studies in Korean houses. Equation 1 was used to calculate values of K_d based on data from five apartments in B3 with no indication of indoor NO_2 sources. The average pre- and post-retrofit values of K_d were 0.44 and 0.25 h^{-1}, respectively. Consequently, the average K_d of 0.34 h^{-1} was used in subsequent calculations. Adjusted pre-retrofit indoor NO_2 concentrations were calculated as the measured indoor concentrations plus ΔC_i, using the pre-retrofit value of λ_v in equation 1.

For PM2.5, a change in outdoor air concentration of ΔC_0 will change the indoor air PM2.5 concentration ΔC_i by less than ΔC_0 because of indoor PM2.5 depositional losses and removal by the particle filter in the forced air heating and cooling system. From a steady state mass balance

$$\Delta C_i = \Delta C_o \, \lambda_v \, / (\lambda_v + K_d + K_f) \quad (2)$$

where K_f is a constant indicating the rate of PM2.5 removal by filtration. For PM2.5, the assumed value of K_d was 0.09 (Riley et al 2002). The time average rate of particle removal by the filter was calculated from equation 3

$$K_f = \lambda_f F \, \varepsilon \quad (3)$$

where λ_f is the volume normalized rate of airflow through the heating and cooling system. Values of λ_f were calculated for each apartment based on the air flow rates in the product literature for the heating and cooling systems and the apartment volumes and ranged from 4.9 to 9.3 h^{-1}. The parameter F is the fraction of time when the heating or cooling system operated, and ε is the particle removal efficiency of the filter. Values of F were estimated for each apartment from measured temperatures in the supply airstreams of the forced air heating and cooling systems, averaged 0.19 and ranged from 0.05 to 0.72. A value of 0.19, applicable to a low efficiency furnace filter, was assumed for ε (Riley, McKone et al. 2002). The resulting values of K_f ranged from 0.06 to 1.0, with a mean value of 0.27. Adjusted pre-retrofit indoor PM2.5 concentrations were calculated as the measured indoor concentrations plus ΔC_i. A limitation of this analysis is that it does not correct for changes in F that area consequence of differences between pre-retrofit and post-retrofit weather conditions.

Other than formaldehyde and acetaldehyde, no individual VOCs had concentrations near guidelines or standards, thus, the concentrations of all VOCs that had concentrations above detection limits were summed. In general, the sums included approximately 30 quantified VOCs. These VOCs are listed in Table S1 in the supplemental information section of Noris, Adamkiewicz et al. (2013). The percent improvements in the summed concentrations were used as a general indicator of the effects of the retrofits on indoor VOCs, recognizing that health risks are not proportional to the summed VOC concentration because the toxicity of VOCs varies widely. Outdoor air concentrations of VOCs were often below detection limits, thus, outdoor air concentrations were not subtracted from indoor air concentrations.

2.4 Evaluation of effects of retrofits on energy consumption

2.4.1 Basic strategy

Residents of study apartments and of similar un-retrofit control apartments from the same apartment buildings provided access to utility web sites from which monthly electricity and natural gas energy use data were obtained for a one year period before and after the retrofit periods. Moves by tenants reduced the amount of data available to less than a full year in several cases, and for a few apartments data were too limited for use. Also, data became unavailable for unknown reasons in some apartments, possibly because utility accounts were transferred to others. The loss of access to data was most pronounced for B1. Usable data were available from only three of five study apartments in B1, and for some analyses usable data were available only for two of five study apartments. Percentage changes in energy use of study apartments minus percent changes in energy use of sets of control apartments located in the same building were the primary indication of the effects of retrofits on energy consumption.

2.4.2 Energy data analyses

For analyses of annual energy use, energy data were analyzed from 12 monthly billing periods before the retrofits and from 12 corresponding (i.e., same range of dates) monthly billing periods after the retrofits. Data were excluded from any billing period that overlapped with the retrofit implementation period by more than two days. When less than 12 months of data were available from either the pre- or post-retrofit periods, the analyses employed the same amount of data and same periods of data from before and after the retrofits. (Because billing periods varied slightly, the initial and final dates of pre-retrofit and post-retrofit data often differed by 1-3 days.) For inclusion in the annual analyses, data were required for at least 300 days before and after retrofits. Annual total gas and electricity use were calculated and divided by the elapsed days.

Summer and winter seasonal energy were also calculated, again employing data from matched pre- and post-retrofit billing periods and dividing total seasonal energy use by billing days. Energy data from billing cycles between October 31 and March 18 were totaled for winter, and energy data from billing cycles between the June 4 and October 3 were totaled for summer. Actual days of data within these time windows varied depending on the utility's billing dates and were nominally either 120 or 90 days. For inclusion in analyses, at least 90 of 120 days, or 57 of 90 days, of data were required from both the pre-retrofit and post retrofit period.

For every annual or seasonal calculation of energy use, the corresponding heating and cooling degree days for the study city were obtained from the Weather Underground web site <http://www.wunderground.com/history/>. This web site used 18.3 °C as the based for heating degree days and 29.4 °C as the base for cooling degree days. Degree days for Oakland, CA were used for B2, located nearby in Richmond, CA.

For each study and control apartment, the percent change in energy use (post-retrofit period use minus pre retrofit period energy use, divided by pre-retrofit period energy use, multiplied by 100%) was calculated. Total pre-retrofit and post-retrofit energy use for each set of study apartments (e.g., B1 study apartments) or control apartments (e.g., B1 control apartments) were also calculated, divided by the number of apartments in the set, and the corresponding percent changes were calculated. These totals were used because simple averages of the percentage changes in the individual apartment energy use data were sometimes highly influenced by the large percentage changes from apartments with small energy use.

Pre-retrofit energy use, and changes in energy use, often varied highly among the apartments within each set of study or control apartments. Consequently, the previously described percentage changes in total energy use were often highly affected by outliers -- large changes in the energy use of individual apartments. Therefore, in "n-1" analyses, the percentage changes in total energy use were also calculated after excluding the data from the apartments with the largest percentage change in energy use within each set. This calculation was not performed for B1 apartments, because even before excluding data, energy use was available from only three (and in some cases only two) apartments.

2.5 Outreach

Outreach activities included writing of technical reports and papers and making them broadly available, technical presentations at meetings, and development of a project website http://apartmentenergy-ieqretrofits.lbl.gov/. Communications with the project's large Technical Advisory Committee served as a form of outreach because advisory committee members were influential individuals in the multi-family housing industry. A project brochure was prepared and distributed to stakeholders from governmental agencies, utilities, non-profits, and retrofit companies that address retrofits in apartments. A webinar was held for stakeholders from the same organizations.

CHAPTER 3: Results

3.1 Retrofit selection protocol and its application

3.1.2 Selected apartments

Five apartments were retrofit in B1, five in B2 (plus a sixth that did not complete post retrofit measurements) and six apartments were retrofit in B3. The apartments from B1 had three or four bedrooms (3BR or 4BR), gas heat, and gas stoves. The apartments were all two-stories with similar layouts except for the bedroom configuration. All apartments had rooftop packaged units for heating and cooling, natural draft gas water heaters in an internal closet on the second floor, and double-pane windows. The kitchen range hoods were not vented to outdoors and the gas cooking ranges had pilot lights. Visible mold or moisture damage in a few of the bathrooms suggested inadequate airflow in bathroom exhaust fans.

The size, layouts, and energy-related features of apartments in B2 varied. The apartments retrofit included one one-bedroom (1BR) apartment (B2A1 for building 2 apartment 1), one 2BR (B2A2) apartment, three 3BR apartments (B2A3, B2A4, B2A5) and one 4BR apartment (B2A6). Apartment B2A1 had a gas wall furnace, while all other apartments had gas forced-air central furnaces located in an internal closet. B2A1 had no bathroom exhaust fan; all other bathrooms had fans. Apartments had range hoods vented to outdoors, but with low air flow rates. B2A4, B2A5 and B2A6 had individual natural-draft gas water heaters, while the other apartments shared a water heater with other apartments. The 3BR and 4BR apartments had two stories; 1BR and 2BR apartments had one story. B2A1 and B2A2 had single-pane sliding glass doors. All windows were double pane. The attic insulation in four of the five top-floor apartments was missing or only a few centimetres thick. None of the apartments in B2 had air-conditioning.

In B3, four 2BR apartments (B3A1, B3A2, B3A3, B3A4) and two 3BR apartments (B3A5, B3A6) were selected. All had rooftop packaged heating and cooling systems, natural-draft gas water heaters in outdoor closets, and electric cooking ranges. They also all featured single-pane sliding glass doors and windows that sometimes did not seal properly as well as kitchen range hoods and bath exhaust fans with inadequate flows.

Table 2 provides energy related characteristics of the 16 retrofit apartments. Sufficient energy data were available from 13 of the apartments, both before and after the retrofit periods, for inclusion in the energy analysis.

Table 3: Basic energy-related characteristics of study apartments

Apartment	Bed-rooms	Floor Area (m^2)	Occu-pants	External Envelope Surfaces	Air Condition-ing	Cooking Fuel	Water Heating Fuel
B1A1	4	92	4	3	Yes	Gas	Gas
B1A2[a]	3	85	3	4	Yes	Gas	Gas
B1A4	3	85	4	3	Yes	Gas	Gas
B1A5	4	92	5	4	Yes	Gas	Gas
B1A6	3	85	5	3	Yes	Gas	Gas
B2A1[a,b]	1	67	1	3	No	Gas	Gas[c]
B2A2	2	76	2	3	No	Gas	Gas[c]
B2A3[a]	3	125	4	4	No	Gas	Gas[c]
B2A4	3	125	3	4	No	Gas	Gas
B2A5	3	125	3	3	No	Gas	Gas
B2A6	4	139	7	4	No	Gas	Gas
B3A1	2	80	2	2	Yes	Electricity	Gas
B3A2	2	80	1	3	Yes	Electricity	Gas
B3A3	2	80	5	4	Yes	Electricity	Gas
B3A4	2	80	3	3	Yes	Electricity	Gas
B3A5	3	98	4	3	Yes	Electricity	Gas
B3A6	3	98	4	4	Yes	Electricity	Gas

[a]excluded from energy analyses due to insufficient energy data
[b]no post-retrofit IEQ data due to tenant move
[c]shared water heater's gas use not part of energy bill

3.1.3 Selected retrofits and their costs

Table 3 identifies the retrofits implemented in each apartment, the average retrofit costs, and also indicates the expected impacts of retrofits on apartment energy use and IEQ conditions.

To provide whole-apartment ventilation, small energy recovery ventilation systems (ERVs) were installed in the living room of each apartment in B1 and in half the apartments in B3. This ERV has slightly larger exhaust airflow than supply airflow. However, compared to an exhaust ventilation fan, use of the ERV should result in less air transport from surrounding apartments into the subject apartment. In all the apartments in B2 and the remaining three apartments in B3, continuously operating bathroom exhaust fans were selected for whole-apartment ventilation. Continuous operation of bathroom exhaust fans in apartments within B2 was not implemented until all IEQ and energy data had been collected and not implemented in apartments in B3 until after IEQ data were collected. ERVs were not used in B2 to avoid disturbance of asbestos in ceilings and because the projected energy benefits of an ERV were small in B2's mild Bay-Area climate. ERVs were installed in three apartments in B3, and exhaust fans in the other three apartments, to enable a performance comparison. The existing kitchen range hoods and bathroom exhaust fans were replaced in all apartments in all buildings since they did not meet the requirements of ASHRAE Standard 62.2 (ASHRAE 2010). An exception was B2A1 which did not have a bathroom exhaust fan, only an operable window; however, the resident refused installation of an appropriately located exhaust fan.

Installation of kitchen and bath fans in B1 and B2 created a situation in which the apartments were predicted to fail the worst-case depressurization test designed to protect against combustion appliance backdrafting. Even without additional air sealing, the higher flows of the new exhaust fans were predicted to cause depressurization levels exceeding the 2 Pascal limit specified by Building Performance Institute (BPI) for natural draft water heaters in some of the apartments. In B2, the water heaters were located in closets adjacent to external walls that had vents to outdoors. The backdrafting risk was eliminated by weather-stripping the closet doors to isolate the appliance from the occupied area of the home. This approach was not applicable in B1 apartments which had water heater closets located far from external walls. Installation of power vent water heaters, which use a blower to establish draft and therefore are less sensitive to house depressurization, was deemed unsuitable because the blowers are noisy and the water heaters were located close to bedrooms. Options in B1 were additionally constrained by air quality regulations that limit nitrogen oxides emissions from new water heaters to 10 ng J^{-1} for storage water heaters with burners up to 22 kW (75,000 Btu/h). The selected option was to install 76,000 Btu/h, 90% efficient condensing water heaters. The high cost of this retrofit option ($3280 installed) resulted in a low cost-normalized benefit score. This experience highlights a need for better products to meet this challenge. There is a need for energy efficient water heaters that are power-vented and quiet enough to be located in closets within the occupied space. Additionally, as more areas impacted by outdoor air pollution require ultra-low NO_X burners, the need and the market for products that also feature these burners will increase.

Several different measures were undertaken to improve the apartment envelopes. In all apartments in B2 and B3, caulks and foams were used to seal accessible penetrations in the envelope created by plumbing, gas lines, electrical boxes and outlets, and at other penetrations through the building envelope such as at the perimeter of window or door frames. To not aggravate the combustion pollutant backdrafting risk in B1 apartments, only the entry doors were weather-stripped. For the apartments in B2 and B3 on the top floor with missing or only a small amount of attic insulation, the attic insulation was upgraded to R-38 by blowing in cellulose insulation. In B2, addition of external wall insulation was originally specified based on inspections with a 1.9 mm boroscope indicating that insulation was absent. However, when the contractor crew drilled the larger holes to inject insulation, they discovered that the majority of the walls had a low level of insulation. Because adding blown-in insulation into wall cavities with existing insulation is challenging (e.g., numerous holes must to be made in walls to homogeneously fill each cavity) and anecdotally considered ineffective, the measure was dropped. This experience suggests that presence of insulation may not be accurately assessed using a small boroscope and that several walls should be checked. In B2A1 and B2A2 with single-pane sliding glass doors, the doors were replaced with double-pane sliding glass doors. In B3, all the windows and sliding doors were single pane. However, due to budget constraints, only selected bedroom windows were replaced. Window and sliding door replacement should both save energy and improve comfort (reducing drafts and radiant heat loss), but their high cost lowered their cost-normalized benefit scores.

In all the apartments with central forced-air HVAC systems, the existing particle filters were replaced with filters having minimum efficiency reporting value (MERV) equal or greater to MERV-11 as determined by ASHRAE Standard 52.2 (ASHRAE 2012). The HVAC duct leakage rates in all the apartments in B2 and some apartments in B3 were high; therefore, the return plenum was sealed and accessible ductwork replaced. For B2 and B3, located where outdoor particle concentrations are frequently elevated, the installation of High-Efficiency Particulate Air (HEPA) filters received a good cost-normalized benefit score despite their energy use (6 - 47W depending on fan speed), thus, HEPA filters were installed in all the apartments and mounted on walls. The occupants of all the apartments were provided portable fans. For the apartments with air-conditioning (B1 and B3), the air movement achievable with the fans may lead the tenants to reduce the use of the air conditioning and save energy during the cooling season, while in B2 (no air-conditioning) the fans may improve comfort. In B1, the rooftop packaged heating and air-conditioning systems were replaced to enable qualification for a utility rebate, conditional to a Home Energy Rating System rating predicting at least 20% energy savings. All incandescent light bulbs were replaced with fluorescent light bulbs that use less energy. In B1, the gas ranges with pilot ignition (that are both an energy waste and a pollution source) were replaced with an electronic ignition gas ranges. In all apartments in all buildings, existing refrigerators were replaced with Energy Star refrigerators. External insulation was added to three existing water heater tanks in B2 and accessible hot water piping was insulated.

The mean predicted energy savings, based on the Home Energy Saver tool and additional estimates, for the apartments in B1, B2 and B3 were 21%, 17% and 27%, respectively. The greater predicted savings for B1 and B3 were partially due to the more severe weather in Sacramento and Fresno, compared to the weather in Richmond. As a consequence of warmer weather, the apartments in B1 and B3 have central air-conditioning providing more energy saving opportunities. The measures that promised the greatest energy savings in B1 were the replacement of the rooftop packaged units for heating and air conditioning and the replacement of the water heater. In B2 and B3, the largest projected energy savings were from addition of attic insulation and HVAC ductwork replacement. Where implemented, window and sliding door upgrades were projected to save significant energy.

Table 4: Retrofits implemented in each apartment

Building 1, Apartment Numbers	Average Installed Cost ($US)	B1A1	B1A2		B1A4	B1A5	B1A6
Weather-strip entry doors	NA	e+ i-	e+ i-		e+ i-	e+	e+ i-
Replace packaged heating and cooling system with more efficient unit	$4060	e+ c+	e+ c+		e+ c+	e+ c+	e+ c+
Replace natural draft water heater with more efficient condensing unit	$3280	e+ i+	e+ i+		e+ i+	e+ i+	e+ i+
Replace refrigerator with more energy efficient refrigerator	$813	e+	e+		e+	e+	e+
Replace cook stove with standing pilot with electronic ignition stove	$680	e+ i+	e+ i+		e+ i+	e+ i+	e+ i+
Replace incandescent light bulbs with compact fluorescent bulbs	$7/bulb	e+	e+		e+	e+	e+
Provide portable fan for air movement	$50	e+ c+	e+ c+		e+ c+	e+ c+	e+ c+
Replace kitchen range hood with higher flow unit	$1160	e- i+	e- i+		e- i+	e- i+	e- i+
Add continuous mechanical ventilation with energy recovery ventilator	$1610	e- i+	e- i+		e- i+	e- i+	e- i+
Replace bathroom fan with fan that operates automatically when high humidity	$880	e- i+	e- i+		e- i+	e- i+	e- i+
Install better particle filter in heating and cooling system	$30	i+	i+		i+	i+	i+
Building 2, Apartment Numbers		**B2A1**	**B2A2**	**B2A3**	**B2A4**	**B2A5**	**B2A6**
Seal leaks in building envelope	$667		e+ i-	e+ i-	e+ i-	e+ i-	e+ i-
Replace HVAC ducts and seal return air plenum	$2200		e+	e+	e+	e+	e+
Replace single pane sliding glass door with double pane door	$2450	e+ c+	e+ c+				
Add attic insulation	$1223		e+ c+	e+ c+		e+ c+	e+ c+
Weather strip door of vented closet containing water heater	$120				e+ i+	e+ i+	
Replace refrigerator with more energy efficient refrigerator	$813	e+	e+	e+	e+	e+	e+
Add water heater insulation jacket	$100				e+	e+	e+
Replace incandescent light bulbs with compact fluorescent bulbs	$7/bulb	e+	e+	e+	e+	e+	e+
Replace kitchen range hood with higher flow unit	$1160	e- i+	e- i+	e- i+	e- i+	e- i+	e- i+
Replace bathroom fan with fan that operates when occupant detected	$880	e- i+	e- i+	e- i+	e- i+	e- i+	e- i+
Provide portable fan for air movement*	$50	c+	c+	c+	c+	c+	c+
Install more efficient particle filter in heating and cooling system	$30		i+	i+	i+	i+	i+
Install wall mounted fan-filter system	$813	e- i+	e- i+	e- i+	e- i+	e- i+	e- i+
Building 3, Apartment Numbers		**B3A1**	**B3A2**	**B3A3**	**B3A4**	**B3A5**	**B3A6**
Seal leaks in building envelope	$667	e+ i-	e+ i-	e+ i-	e+ i-	e+ i-	e+ i-
Replace HVAC ducts and seal return air plenum	$2200		e+		e+		e+
Add attic insulation	$1223		e+ c+	e+ c+	e+ c+		e+ c+
Replace single pane window with double pane window	$850	e+ c+				e+ c+	e+ c+
Replace refrigerator with more energy efficient refrigerator	$813	e+	e+	e+	e+	e+	e+
Replace incandescent light bulbs with compact fluorescent bulbs	$7/bulb	e+	e+	e+	e+	e+	e+
Replace kitchen range hood with higher flow unit	$1160	e- i+	e- i+	e- i+	e- i+	e- i+	e- i+
Add continuous mechanical ventilation with bathroom exhaust fan	$880	e- i+				e- i+	e- i+
Add continuous mechanical ventilation with energy recovery ventilator	$1610		e- i+	e- i+	e- i+		
Provide portable fan for air movement	$50	e+ c+	e+ c+	e+ c+	e+ c+	e+ c+	e+ c+
Install more efficient particle filter in heating and cooling system	$30	i+	i+	i+	i+	i+	i+
Install wall mounted fan-filter system	$813	e- i+	e- i+	e- i+	e- i+	e- i+	e- i+

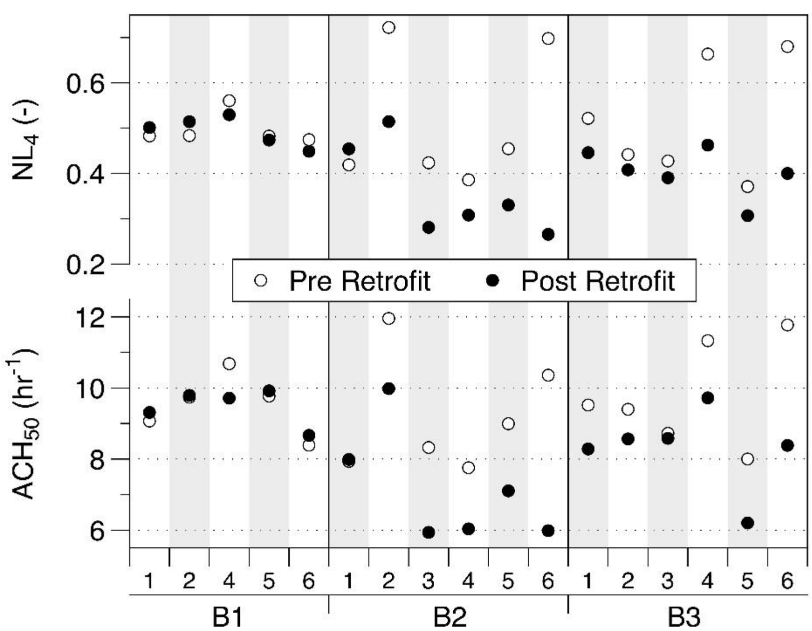
Key: e+ indicates retrofit expected to generally positively affect (reduce) energy use; e- indicates retrofit expected to generally negatively affect (increase) energy use; i+ indicates retrofit expected to generally positively affect (improve) indoor air quality; i- indicates retrofit expected to generally negatively affect (worsen) indoor air quality; c+ indicates retrofit expected to generally positively affect (improve) thermal comfort; empty cell means the retrofit was not implemented.
[a]will not save energy in B2 because B2 has no air conditioning

The total retrofit cost for B1 was approximately $63,400 (average of $12,700 per apartment). This amount exceeded the initial budget target for this building but the inclusion of additional measures increased projected energy savings above the threshold for a utility rebate. The total cost of the retrofits in B2 was $46,100 (average of $7,700 per apartment). The total cost for the retrofits implemented in B3 was $54,000 (average of $9,000 per apartment). Overall, the prices for the different retrofit measures were within the industry typical range. The costs may have been modestly increased due to research project requirements. Building Performance Institute (BPI)-accredited contractor companies were selected to implement retrofits because they must comply with industry voluntary work standards and were expected to be more skilled. Contractors were selected based on quotes, availability to meet the project schedule, and a check of references.

3.1.4 Results of pre- and post-retrofit diagnostics

Figure 1 shows the pre- and post-retrofit envelope leakage from all apartments. The mean pre-retrofit air exchange rate at 50 Pa (ACH_{50}) and normalized leakage at 4 Pa (NL_4) for the apartments that received envelope sealing were 9.7 hr^{-1} and 0.52, respectively. The ACH_{50} is a widely used measure of envelope leakage, although NL_4 is a better indicator of air infiltration rates. In B1, air sealing was not performed to avoid the combustion appliance backdrafting risk, while in B2A1 the contractor was not able to perform air sealing due to the wishes of the resident. The mean post-retrofit ACH_{50} for the apartments that received air sealing was 7.7 hr^{-1}, providing a mean reduction of 20%. The lowest post-retrofit ACH_{50} was 5.9 hr^{-1}, in B2A3. The largest ACH_{50} improvement (42%) occurred in B2A6 which had a broken window replaced by the building manager. For the apartments that received air sealing in B2 and B3, average air leakage reductions were 26% and 15%, respectively. In the B3 apartments with a bedroom window replacement and no ERV installation (B3A1, B3A5, B3A6), the reduction was 21%, substantially greater than the 8% reduction in the other three apartments that received ERVs and no window replacement. The values for NL_4 follow similar trends. The mean post-retrofit NL_4 for the apartments that received air sealing was 0.37, with a mean reduction of 27%.

Figure 1: Air changes per hour at 50 Pa (ACH_{50}) and normalized leakage at 4 Pa (NL_4) measured before and after retrofits.



No work was done to improve envelope airtightness in B1 and B2A1

Figure 2 presents the pre- and post-retrofit airflows for bathroom exhaust fans. None of the pre-retrofit fans had flow rates meeting the 24 L s^{-1} (50 cfm) specification of ASHRAE Standard 62.2 (ASHRAE 2010). The bathroom fans in B1 did not have any flow, probably due to obstructed ducts. Even with the new fans and ducting, the measured airflows were below 24 L s^{-1}. In B2 and B3, the pre-retrofit airflow rates were approximately 9.4 L s^{-1} (20 cfm) while flow rates for all but one of the newly installed fans (main bathroom of B3A5), met the recommendation with the mean airflow exceeding 33 L s^{-1} (70 cfm). The lower post-retrofit flow rates in B1 may be a consequence of the use of a different fan for B1 than in B2 and B3. The new bathroom fans were much quieter than the original fans, a change that may promote fan use and reduce discomfort. The bathroom exhaust fans were operated, or operated above their baseline speed for continuously operating devices, 7% of the time in B1 after the retrofits (no pre-retrofit data available), 9% and 15% of the time in B2 before and after the retrofits, respectively, and 2% and 11% of the time in B3 before and after the retrofits, respectively. The increased use of the bath fans is likely due to the quietness of the new units and the sensors that turn on fans when occupants are sensed or humidity is high.

Figure 2: Bathroom exhaust fan airflows measured before and after the retrofit implementation

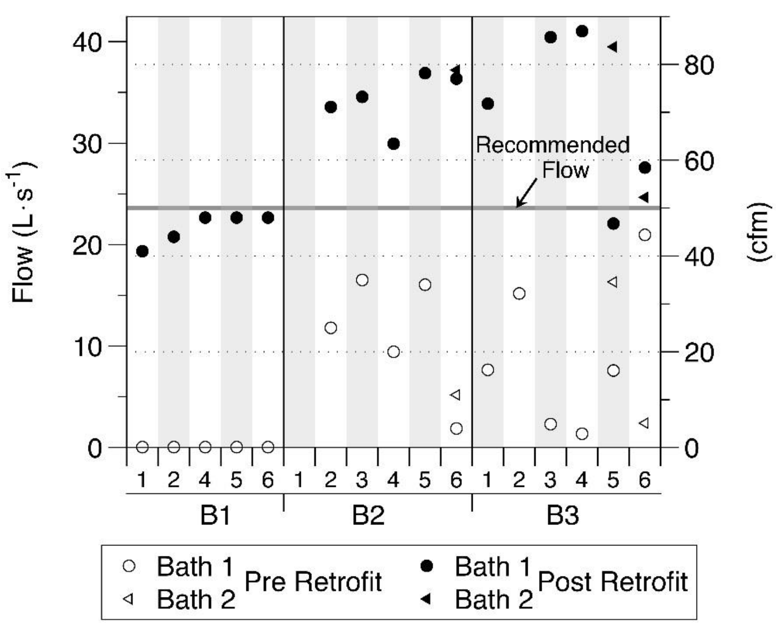
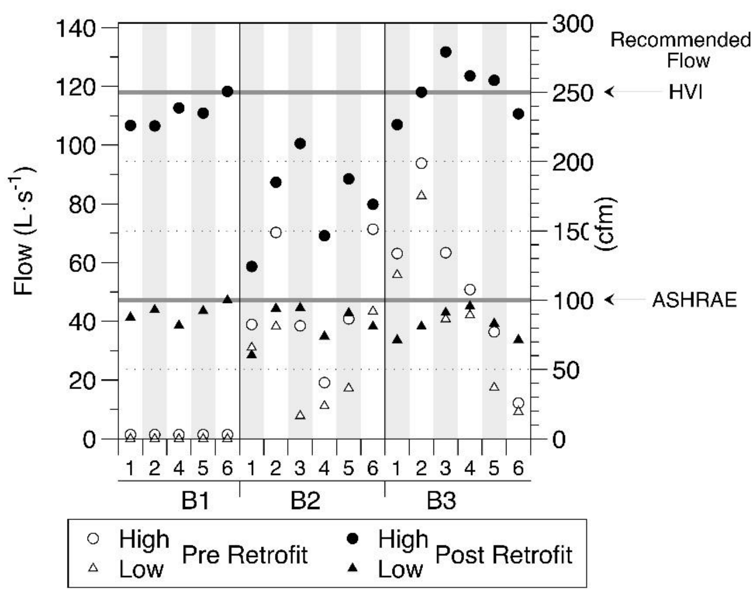


Figure 3 shows the airflow rates of kitchen range hoods for the low and high fan-speed settings, measured before and after the retrofits. The pre-retrofit kitchen range hoods in B1 were not vented to outdoors, providing no exhaust airflow. During the retrofits, new hoods and ducts venting outdoors were installed. The mean post-retrofit airflows in B1 for the low and high settings were 43 L s^{-1} (91 cfm) and 111 L s^{-1} (235 cfm). In B2 and B3, only the range hoods (but not the ductwork) were replaced. The same make and model of kitchen range hood was installed in B1 and B2. The lower airflows observed for the high setting in B2 (mean of 81 L s^{-1} or

171 cfm) compared to B1 are assumed to result from greater airflow resistance in the ducting. At the low fan speed, only one of the installed range hoods reached the 42 L s-1 (100 cfm) airflow required by ASHRAE to correspond to the 3-sone sound limit. Airflow performance at low speed is also relevant because it is the most likely operating condition owing to its quietness relative to other settings. At the high fan speeds, five of 17 range hoods had post-retrofit flow rates meeting the 118 L s-1 (250 cfm) recommendation of the Home Ventilating Institute (HVI). The effectiveness of kitchen range hoods in removing cooking-produced pollutants increases with flow rate, and is also influenced by the geometry of the hood with respect to the burners (Delp and Singer 2012, Singer, Delp et al. 2012).

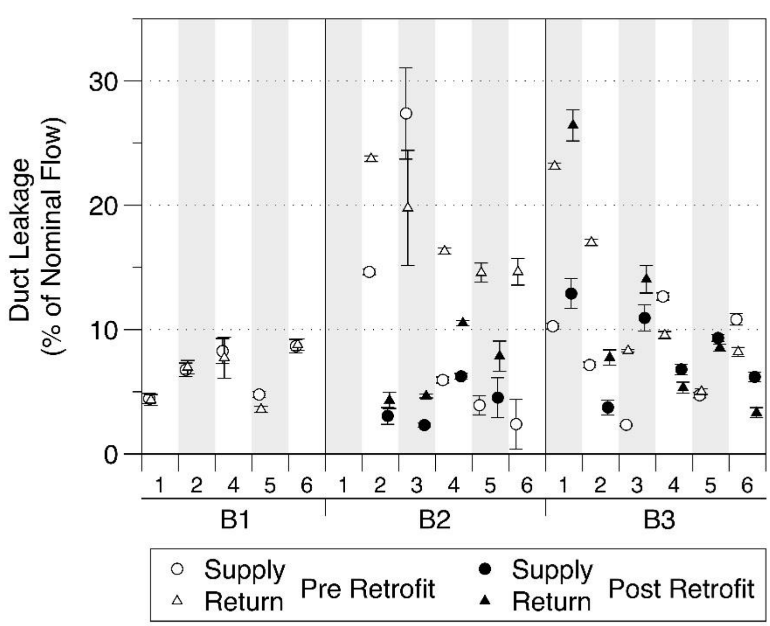
Figure 3: Kitchen range hood airflows at low and high fan speeds, measured before and after the retrofit implementation



Averaged across apartments, the kitchen range hoods were used 6% of the time in B1 after the retrofits (no pre-retrofit data available), for 10% of the time in B2 both before and after the retrofits, and for 5% and 2% of the time in B3 before and after the retrofits, respectively. These data indicate that installation of newer quieter range hood did not increase use. Estimation of operation times of range hoods from pressure sensor data required considerable judgment, and the reported operation times have a high level of uncertainty. Use of the cooking ranges was not monitored thus it was not possible to assess the fraction of cooking events for which range hoods were operated. In the post retrofit survey, the majority (14/16) of households reported "always" using their kitchen fans while cooking, although this behavior may be over-reported.

Figure 4 illustrates the return and supply duct leakage for the study apartments. The mean pre-retrofit return and supply leakages in B1 apartments were 26 L s-1 (55 cfm) and 28 L s-1 (58 cfm), respectively. Since the ductwork was not modified in B1, the post retrofit duct leakage was not measured. B2A1 did not have any ductwork since it had a wall heater, while the other five units in B2 had central air handler units (AHUs) in internal closets with ductwork in the attics; in these five units the return plenums were sealed and all accessible ductwork was replaced. In B2A6, the post-retrofit duct leakage could not be measured because the HVAC system was not functioning when the apartment was visited. The mean return and supply duct leakages before the retrofits in B2 were 88 L s^{-1} (185 cfm) and 50 L s^{-1} (105 cfm), respectively, indicating great losses on the return sides partially due to noticeable gaps in the return plenums. The mean return and supply duct leakages for B2 apartments after the retrofits were 35 L s^{-1} (73 cfm) and 21 L s^{-1} (43 cfm), respectively corresponding to reductions of 60% and 38%. Considerable reductions in leakage were observed for A2 (82% return and 79% supply) and A3 (76% return and 92% supply) – in these cases the initial leakage rates were high suggesting that larger holes, that are more likely to be found, may have been present. In B3, only apartments A2, A4 and A6 received duct replacement since A1 and A5 had the majority of the ductwork inside the wall cavities, while A3 had much lower initial leakage. The mean pre-retrofit return and supply duct leakages in all B3 apartments were 47 L s^{-1} (99 cfm) and 33 L s^{-1} (69 cfm). The mean return and supply duct leakage reductions for the three apartments that received duct replacement and return plenum sealing were 53% and 40%. In the remaining three apartments, there was an increase in duct leakage, partially explainable by the uncertainty of the delta Q test. Additionally, the pressure changes resulting from the replacement of low efficiency filters with high efficiency filters might have increased duct leakage rates.

Figure 4: Pre- and post-retrofit duct leakages expressed as percentage of HVAC system nominal flow



All families (17) completed at least one enrollment survey per household, and most completed at least one pre-retrofit (16/17) and one post-retrofit (16/17) survey per household. While the sample size limits the quantitative conclusions that can be drawn from these data, some trends are worth noting. At baseline, only one household rated their air quality over the past month as "very acceptable" (on a four-level scale which included "somewhat acceptable", "barely acceptable" and "not acceptable"), as compared to eleven households giving this rating post-retrofit. All families reported being either "very satisfied" (15/16) or "generally satisfied" (1/16) with the retrofit work in general (on a four-level scale which also included "generally dissatisfied" and "very dissatisfied"). Similar results were found when household members were asked about satisfaction with individual retrofit components (e.g., fans, range hoods, lighting, etc.), with the majority reporting being "very satisfied." While few households reported any dissatisfaction, two of the three households who received continuously vented bath fans reported some dissatisfaction with the associated noise level.

3.2 IEQ conditions

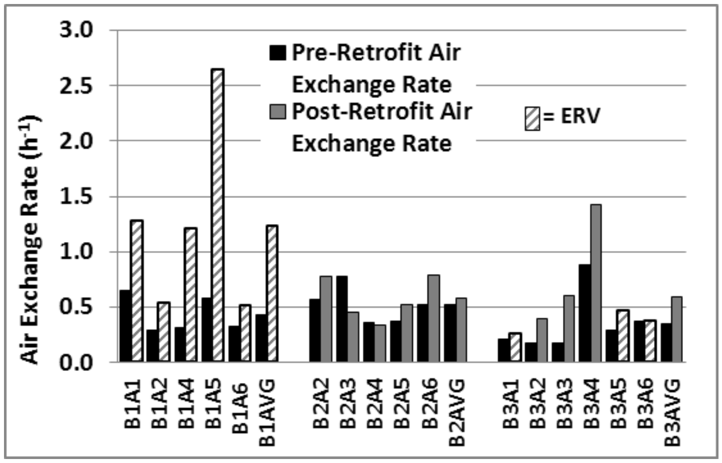
3.2.1 Data tables

Tables S2 – S4 in the supplemental information section of Noris, Adamkiewicz et al. (2013) provide the main IEQ measurement results from periods before and after the retrofits for apartments in buildings B1 through B3, respectively. These tables provide for each apartment, for both pre-retrofit and post-retrofit periods, values of the IEQ parameters described in the methods section. When applicable, outdoor air values of parameters are also provided. Carbon monoxide concentrations were consistently below guidelines and near to the level of measurement uncertainty, thus, these data are not included. Because the large amount of tabulated data in S2 – S4 does not facilitate easy communication of study findings, the findings are illustrated in the subsequent figures.

3.2.2 Air exchange rates

Figure 5 shows the measured air exchange rates. In this figure and in Figures 6-13, solid columns represent data from apartments without continuous mechanical ventilation and patterned columns represent data from apartments with continuous mechanical provided by energy recovery ventilators (ERVs) in the post retrofit data collection periods. Air exchange rates increased by 180% in B1 (with ERVs installed), by 11% in B2 without ERVs (not a significant change given measurement uncertainty), and by 68% in B3 which had ERVs installed in A2, A3, and A4. Only one of three B3 apartments without an ERV installed (B3A5) had a notable increase in air exchange rate.

Figure 5: Air exchange rates

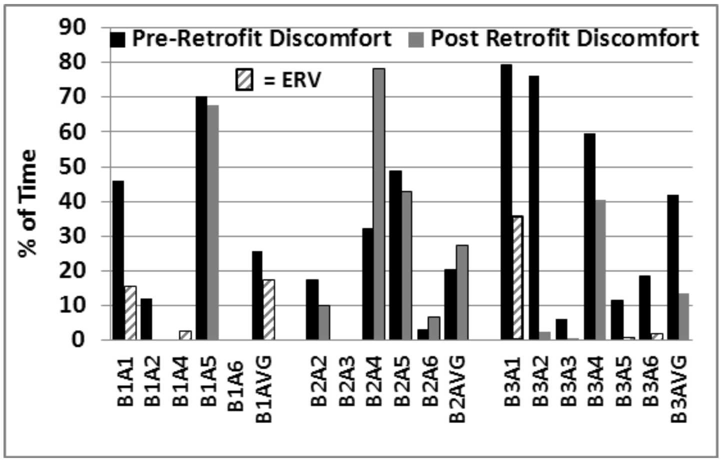


3.2.3 Thermal comfort and humidity

The retrofits that may have affected thermal comfort include envelope sealing, attic insulation, replacement of windows and sliding glass doors, duct sealing or replacement, and replacement of heating and cooling systems. The calculated values of the metrics relevant to thermal discomfort are plotted in Figure 6. In B1 and B3, after the retrofits there was substantially less time with temperatures above (in B1) or below (in B3) the boundaries of ASHRAE thermal comfort zone. Thus, the retrofits appear to have improved comfort in these buildings. In B2 there was a modest increase in time with temperatures outside of the comfort zone, indicating discomfort. These findings remained after considering only daytime (07:00 – 23:00) temperature data (results not shown). Results from B3 should be viewed with caution, because the average outdoor air temperature was 14.6 ^{o}C after the retrofits compared to 8.1 ^{o}C before retrofits.

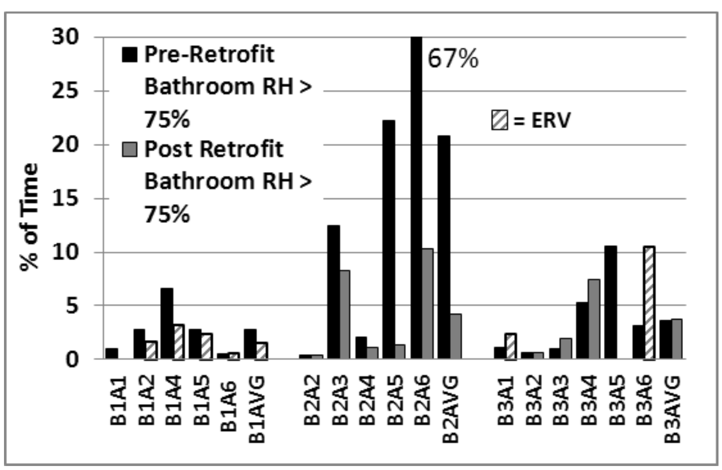
Also examined were the hours of overcooling in B1 (studied in summer) and overheating in B2 and B3 (studied in winter), relative to the boundaries of ASHRAE's summer and winter thermal comfort zones, at 50% relative humidity. In B1, temperatures were below 21 ^{o}C, the approximate lower boundary of ASHRAE's summer thermal comfort zone, 1% of the time before the retrofits and 4% of time after the retrofits. In B2, temperatures exceeded 25.5 ^{o}C, the approximate upper boundary of ASHRAE's winter comfort zone, 17% of the time before the retrofits and 13% of time after the retrofits. In B3 the percent time with indoor temperatures above 25.5 ^{o}C increased from 4.3% to 9.4%. In all cases, the changes were small.

Figure 6: Percentages of times with temperatures above (B1) or below (B2 and B3) the temperature boundaries of the ASHRAE thermal comfort zone



In most apartments, bathroom RH exceeded 75% only a few percent of the time (Figure 7). In B1 and B2, the percent of time with bathroom RH greater than 75% was generally less after the retrofits, potentially indicating the beneficial effect of the bathroom fans that came on automatically when bathroom RH was high (B1) or when an occupant was detected (B2). In B3, the periods of high RH were small, and, on average, increased slightly after the retrofits possibly because the moisture content in outdoor air was 75% higher after the retrofit (0.0065 versus 0.0037 gram water per gram dry air). Before the retrofits, in three B2 apartments the bathroom RH exceeded 75% more than 20% of the time. In each of these cases, the periods of high RH were much reduced after the retrofits.

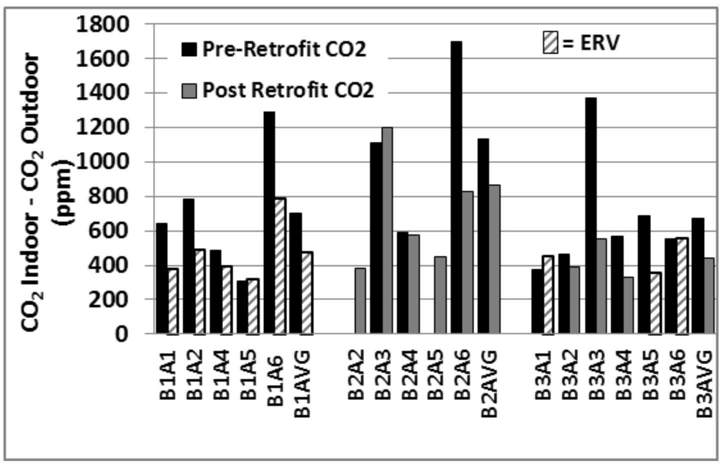
Figure 7: Percentages of times with bathroom relative humidity greater than 75%



3.2.4 Contaminant concentrations

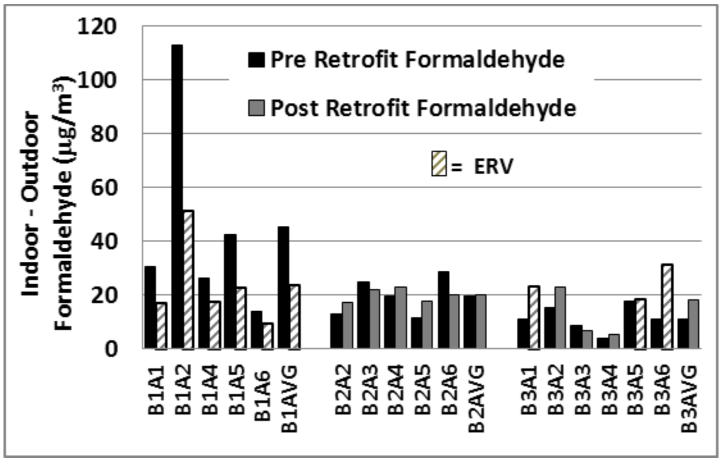
Carbon dioxide concentrations are higher indoors because CO_2 is released by occupants and cooking. Figure 8 shows that the difference between indoor and outdoor CO_2 concentration decreased in most apartments. The average decreases were 33%, 24%, and 35% in B1, B2, and B3, respectively. At these concentrations, CO_2 is not believed to directly pose any health risks; however, it is a proxy for unmeasured indoor-generated pollutants with emission rates linked to occupancy. In many cases, indoor minus outdoor concentrations exceeded 600 ppm. Many practitioners assume ventilation rates are insufficient when indoor CO_2 concentrations exceed 1000 ppm, corresponding to indoor-outdoor concentration differences exceeding approximately 600 ppm.

Figure 8: Carbon dioxide concentrations



Formaldehyde is emitted from a range of indoor sources with manufactured wood products as a major source. Formaldehyde has been declared a human carcinogen by the International Agency for Research on Cancer. As shown in Figure 9, in B1, the average indoor minus outdoor formaldehyde concentration decreased by 48% from 45 $\mu g\ m^{-3}$ before the retrofits to 24 $\mu g\ m^{-3}$ ppb after the retrofits. In B2, the average pre- and post-retrofit indoor minus outdoor formaldehyde concentrations, 19.5 and 20.0 $\mu g\ m^{-3}$, were no different considering measurement uncertainty. In B3, the average indoor minus outdoor formaldehyde concentration increased 64% from 11 to 18 $\mu g\ m^{-3}$. Indoor concentrations exceeded California EPA's acute reference exposure level (REL) of 9 $\mu g\ m^{-3}$ in all but one apartment, always exceeded the California EPA's chronic REL of 3 $\mu g\ m^{-3}$, and in one apartment exceeded the World Health Organization's short and long-term guideline of 100 $\mu g\ m^{-3}$. Changes in ventilation rates, temperatures and humidity may partially explain the changes in indoor formaldehyde concentrations.

Figure 9: Formaldehyde concentrations



Acetaldehyde sources include cooking and outdoor air. The U.S. EPA classifies acetaldehyde as a probable human carcinogen. Acetaldehyde concentrations (Figure 10) were consistently well below California EPA's chronic reference exposure level of 140 µg m^{-3} but, in all except one apartment, exceeded the U.S. EPA's reference concentration for inhalation exposures of 9 µg m^{-3} based on respiratory toxicity. On average, the indoor minus outdoor concentration difference decreased 49%, 12%, and 35% in B1 through B3, respectively. The retrofits that may have decreased acetaldehyde concentrations include the range hood replacements and installation of continuous mechanical ventilation systems in apartments in B1 and in apartments 2, 3, and 4 in B3.

Figure 10: Acetaldehyde concentrations

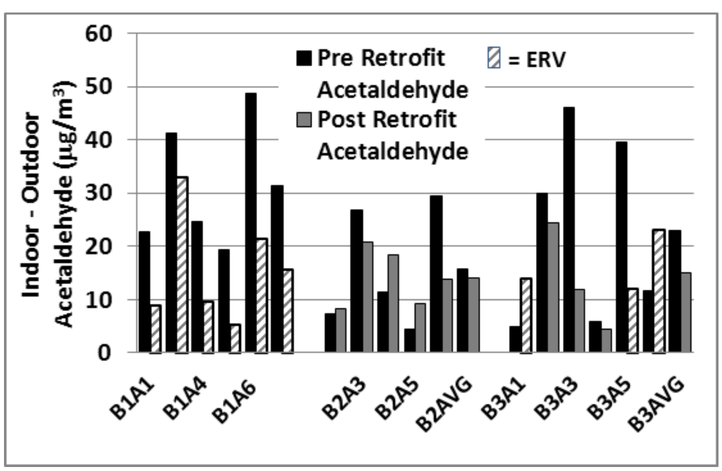
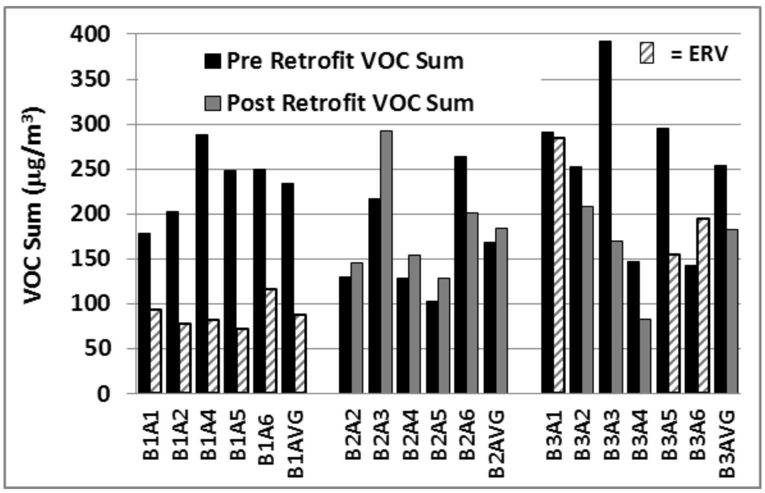


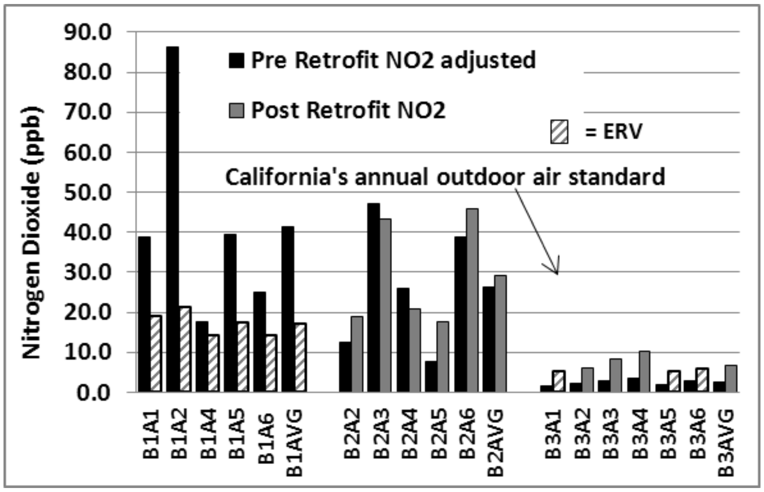
Figure 11 shows the summed indoor VOC concentrations, excluding formaldehyde and acetaldehyde. The average concentration decreased 62% in B1, increased 10% in B2, and decreased 28% in B3. Concentrations of individual VOCs were well below applicable guidelines; thus, the implications of these VOCs for health are not well understood. Health risks from additive or synergistic effects of multiple VOCs are a possibility. The retrofits that may have affected the summed VOC concentration are the same as listed above for acetaldehyde. In addition, education of tenants about the importance of cleaning products and air fresheners as a source of VOCs might have affected indoor concentrations.

Figure 11: Summed VOC concentrations



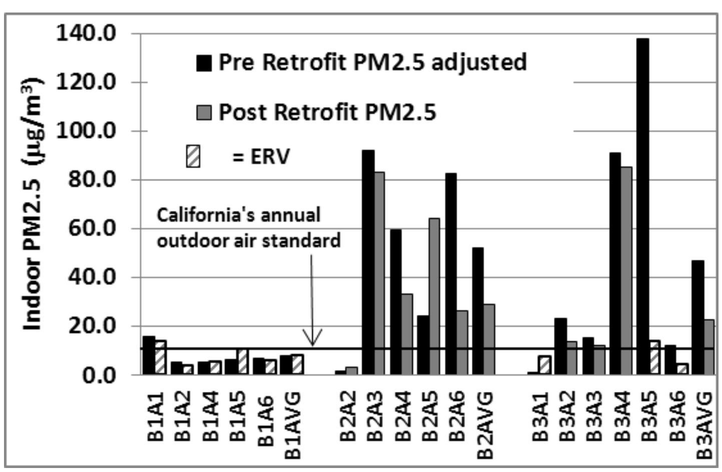
Higher levels of NO_2 are linked to respiratory health effects, particularly in children. California's outdoor air standard is 30 ppb as an annual average. Indoor air concentrations in most apartments were below this standard, but two apartments had pre-retrofit indoor air concentrations, before the adjustments for changes in outdoor air concentrations, above 50 ppb. The results of the NO_2 measurements, after the above-mentioned adjustments, are shown in Figure 12. NO_2 sources include outdoor air and indoor combustion. The importance of the indoor sources, raising indoor concentrations above those outdoors, was most evident in B1 which had gas stoves. In the pre-retrofit period the stoves had standing pilot lights. The average indoor concentration decreased 58% after the retrofit, presumably because of replacement of the stove to eliminate the pilot lights, addition of range hoods that vented to outdoors, and increases in apartment ventilation rates. Apartments in B2 had gas stoves without pilot lights and apartments in B3 had electric stoves. NO_2 concentrations increased 11% in B2, an insignificant increase given measurement uncertainties. In B3, the average concentration increased 169%, from 2.5 to 6.8 ppb; however, at these low concentrations the measurement uncertainty is very high.

Figure 12: Nitrogen dioxide concentrations



PM2.5 in outdoor air is linked to a broad range of adverse respiratory and cardiovascular health effects. Key sources of indoor PM2.5 include outdoor air, indoor combustion, and cooking. Vacuum cleaning and resuspension from surfaces can also be particle sources. The outdoor air standard for PM2.5 in California is 12 µg m^{-3}. PM2.5 concentrations are provided in Figure 13. In B1, indoor concentrations of PM2.5 (unadjusted) were generally well below this standard, while in B2 and B3 concentrations were usually well above the standard and as high as 160 µg m^{-3} before adjustment. After the adjustments for changing outdoor air concentrations, average indoor PM2.5 concentrations decreased 2% (insignificant given measurement uncertainty), 44%, and 51% in B1 through B3 respectively. The retrofits that may have contributed to changes in indoor PM2.5 include replacement of range hoods, upgrading of filters in forced air heating and cooling systems, addition of continuous mechanical ventilation in apartments in B1 and in apartments 2, 3, and 4 in B3, installation of wall mounted air cleaners in B2 and B3, and education of tenants about particle emission from burning incense.

Figure 13: PM2.5 concentrations



3.2.3 Relationship of air exchange rates with indoor air quality

The relationships of changes in pollutant concentration with change in air exchange rate is shown in Figure 14 for CO_2, formaldehyde, acetaldehyde, and the sum of 30 VOC. An overall trend is evident with a larger percent increase in air exchange rate associated with a larger decrease in indoor (or indoor minus outdoor) pollutant concentration. In almost all cases with more than a 50% increase in air exchange rate, these IEQ parameters improved. However, data from individual buildings do not always show the same trends with air exchange rate, potentially because indoor pollutant emission rates were not constant. Occupancy, tenant behaviors, and temperature and humidity are factors that influence emission rates of these pollutants. Also, one should keep in mind the fact that the measured air exchange rates included air from outdoors and from surrounding apartments.

Figure 14: Relationships of pollutant concentrations with air exchange rates

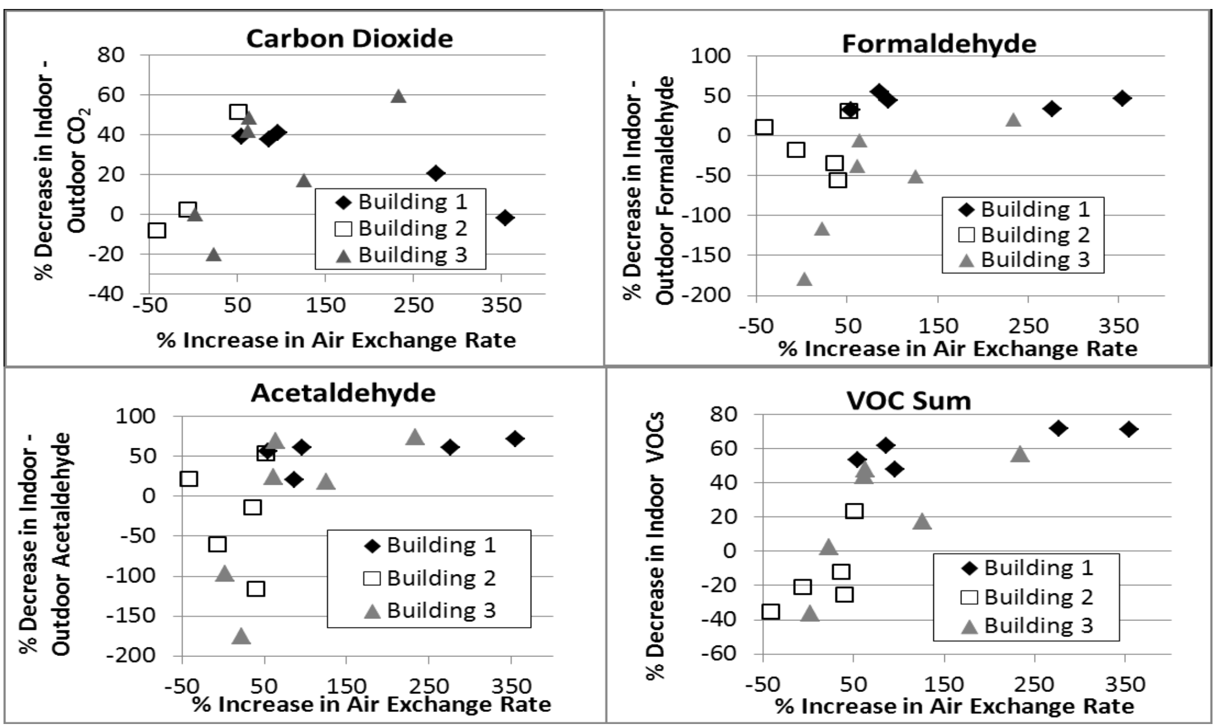
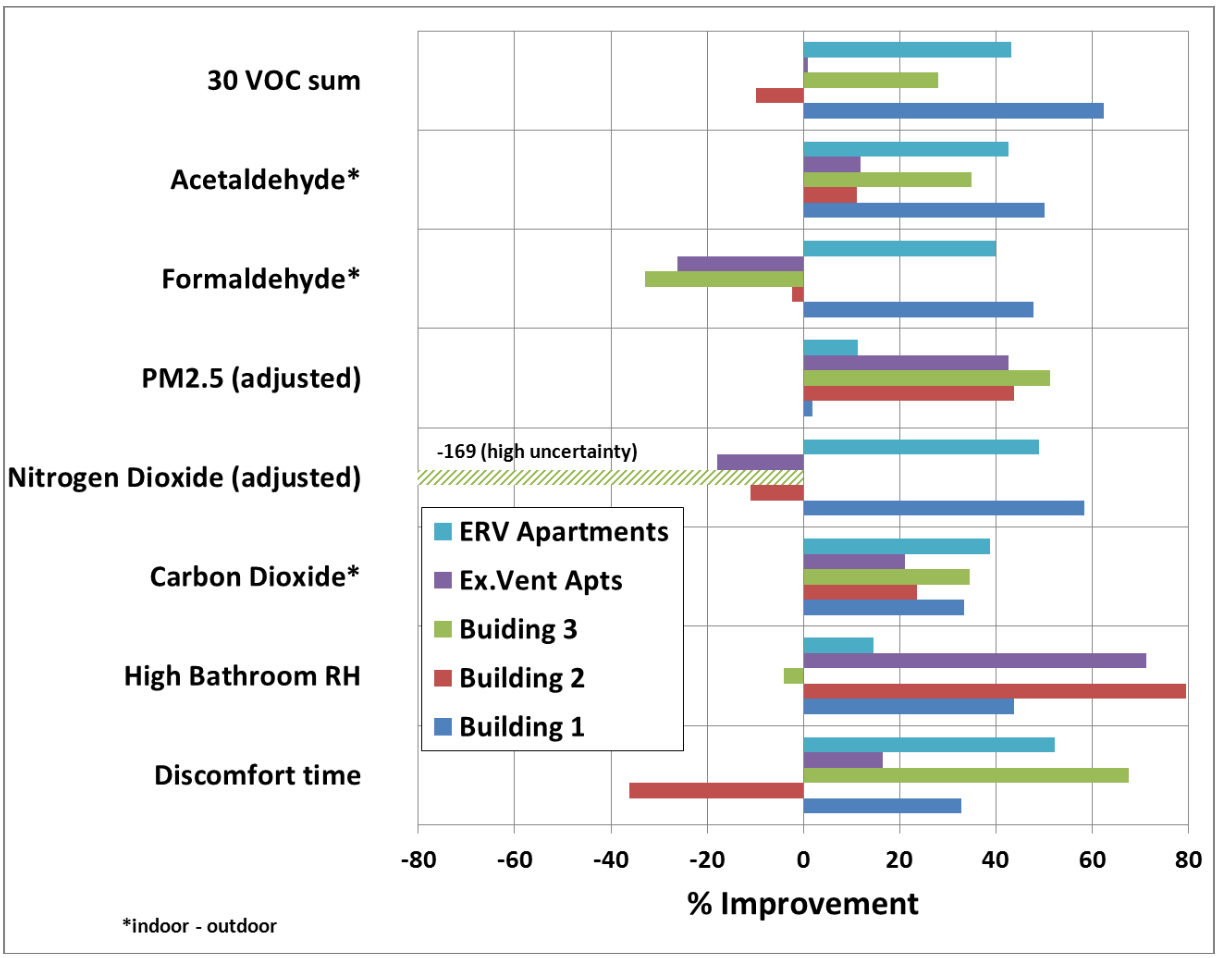


Figure 15 shows overall percent change of IEQ metrics for each building, for all apartments with ERVs providing continuous mechanical ventilation (ERV apartments), and for all apartments that had intermittent bathroom exhaust ventilation fans (Ex.Vent apartments) but no continuous mechanical ventilation. The changes in the comfort and humidity metrics in B3 should be viewed with particular caution because of the substantially higher outdoor air temperature and outdoor air moisture content in the post-retrofit monitoring period. Overall, there are far more improvements than degradations in IEQ metrics. However, results for nitrogen dioxide and formaldehyde are mixed, with some decreases and some increases in indoor concentrations. For pollutants other than PM2.5, apartments with ERVs had better results than apartments without continuous mechanical ventilation. Apartments with ERVs had a smaller improvement in PM2.5 (after adjustments). There are two possible explanations. First, outdoor air is a major source of indoor PM2.5 and the mechanical ventilation in ERV apartments brought in more outdoor air. The ERVs did include particle filters with a MERV 6 rating – these filters when new would be expected to remove less than 35% of the PM2.5 from the incoming outdoor air (Fisk, Faulkner et al. 2002). Second, all Ex.Vent homes had wall mounted particle air cleaners installed but these air cleaners were installed in only three of eight homes with ERVs.

Figure 15: Summary IEQ results



3.2.5 Occupants' perception of indoor air quality

There were 17 complete sets of surveys from the 16 apartments. Twelve of the 17 subjects reported some improvement in overall air quality, with five subjects reporting no change. Three of the five subjects reporting no change were from B3 and one each was from B1 and B2. Because of the very small numbers of subjects, and because the subjects were not blinded, the surveys provide only a suggestion of an overall improvement in perceived air quality.

3.3 Apartment energy consumption

3.3.1 Pre-retrofit energy consumption and its variability

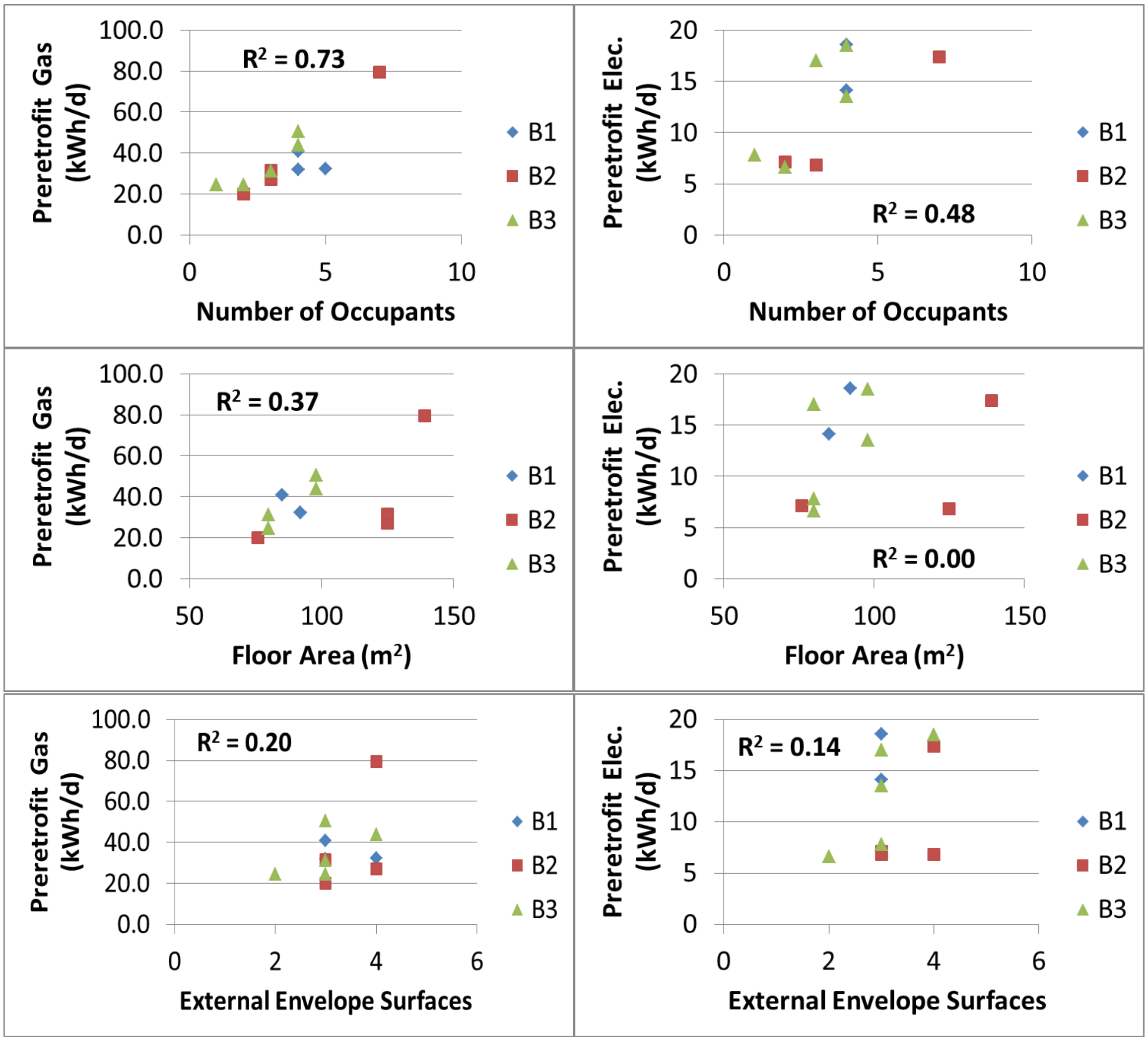
Tables A1 –A9 provide pre-retrofit and post-retrofit gas and electricity energy use per day, for the annual, winter, and summer periods, for each study apartment and each control apartment. The corresponding days within the billing periods, heating degree days, and cooling degree days are provided. It is evident from Table 4, which combines pre-retrofit data from study and control apartments within buildings, that there is a large range in the energy use of the rather similar apartments within the same building, particularly in B2 and B3 where the range is a factor of 2.5 to 4.0.

Table 5: Range in pre-retrofit energy use among apartments within buildings

Apartments, Fuel (number)	Minimum kWh/d	Maximum kWh/d	Ratio (Max/Min)
B1, Gas (n = 8)	27.0	40.7	1.5
B1, Elec (n=8)	6.9	18.6	2.7
B2, Gas (n=11)	11.1	44.5	4.0
B2, Elec. (n=11)	4.7	17.4	3.7
B3, Gas (n=11)	20.5	50.4	2.5
B3, Elec. (n=11)	6.6	26.2	4.0

Figure 16 shows pre-retrofit energy plotted versus occupancy, floor area, and number of external envelope surfaces (walls plus ceiling). Based on the values of R^2 the association with occupancy is most evident. The association of both gas and electricity use with number of external envelope surfaces is weak, with R^2 values 0.20 and 0.14.The building number is a proxy for climate, with B2 having the most moderate climate and B2 apartments having no air conditioning. However, apartments from B2 do not consistently use less energy than apartments from B1 or B3. Clearly, climate differences are not the major driver for the variability in energy use.

Figure 16: Pre-retrofit energy use of study apartments plotted versus number of occupants, floor area, and number of envelope surfaces (walls plus ceiling) exposed to outdoors



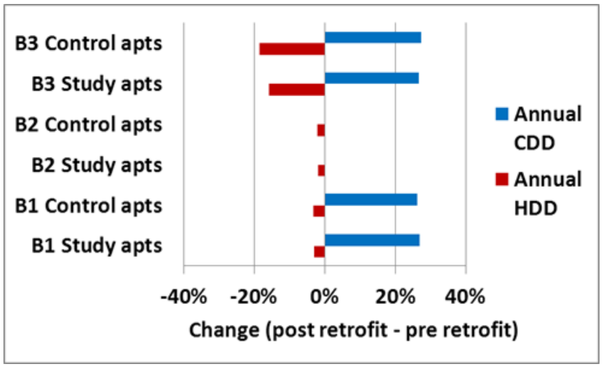
3.3.2 Changes in energy use

Tables A3.1 –A3.9 in appendix A3 provide the percentage change in energy use for each apartment, including control apartments, the percentage changes in total energy use, and the percentage changes in total energy use after omitting outliers via the "n-1" analysis process.

Figure A3.1 in appendix A3 shows the annual energy use data, for apartments in B1 through B3, respectively, and provides the associated percentage changes in energy use. Figure A3.2 provides analogous plots for winter gas consumption and summer electricity consumption. Figure A3.3 illustrates summer gas and winter electricity use; i.e., gas use from a period of essentially no heating degree days (HDD) and electricity use from a period with essentially no cooling degree days (CDD). In these figures, the letter "c" in the apartment code indicates that the apartment is a control apartment that was not retrofit.

Figure 17 shows the percent changes in annual HDD and CDD between the pre-retrofit and post-retrofit periods, for each set of study and control apartments. The small differences between degree days for study and control apartments reflect the differences in dates for which energy data were available. Cooling degree days for B1 and B2 are 26% to 27% higher during the post retrofit year. Cooling degree days are not shown for B2, because it had no air conditioning. Heating degree days for B3 apartments decreased in the post-retrofit year by 16% to 19%, and by a few percent for apartments in B1 and B2. The changes in degree days are nearly identical for study and control apartments. On average the changes in weather should have affected energy use similarly in study apartments and control apartments.

Figure 17: Changes in annual heating degree days (HDD) and cooling degree days (CDD)



Pre-retrofit to post-retrofit differences in energy use in non-retrofit control apartments were substantial. Table 5 shows the ranges and average of the absolute values of the percent changes within the individual control apartments. Changes range from -40% to 102%, with averages of absolute values of percent changes ranging from 11% to 34%.

Table 6: Changes in energy use in control apartments

Apartments (number)	Minimum	Maximum	Average Absolute Value Change
B1 Gas (n = 6)	-4%	28%	11%
B1 Elec (n=7)	5%	102%	34%
B2 Gas (n=7)	-18%	36%	13%
B2 Elec (n = 7)	-15%	22%	11%
B3Gas (n=6)	-40%	21%	19%
B3 Elec (n=6)	-15%	23%	17%

A positive number indicates increased energy use

The overall energy savings, based on change in total energy use per apartment in study apartments minus the change in in total energy use per apartment in control apartments is illustrated in Figure 18. The data suggest gas energy savings, larger in the winter than annually or during the summer. Estimated annual gas energy savings are 25% in B1 but only 7% in B2 and B3. The data indicate a 41% annual electricity savings in B1, but this number is based on only two study apartments versus six control apartments. The data from B2 and B3 indicate 3% and 17% increases (as opposed to expected savings) in annual electricity use of study apartments relative to control apartments. For B3, the percentage increase in electricity use of study apartments versus control apartments is smaller during the summer air conditioning season than for the full year, indicating that increased air conditioning does not likely explain increased electricity use. There is a striking 49% increase in winter electricity use of B3 study apartments relative to B3 control apartments, driven substantially by the changes in electricity use in one study apartment and one control apartment, as discussed subsequently.

Figure 18: Estimated overall energy savings based on changes in energy use of study apartments minus changes in energy use of control apartments

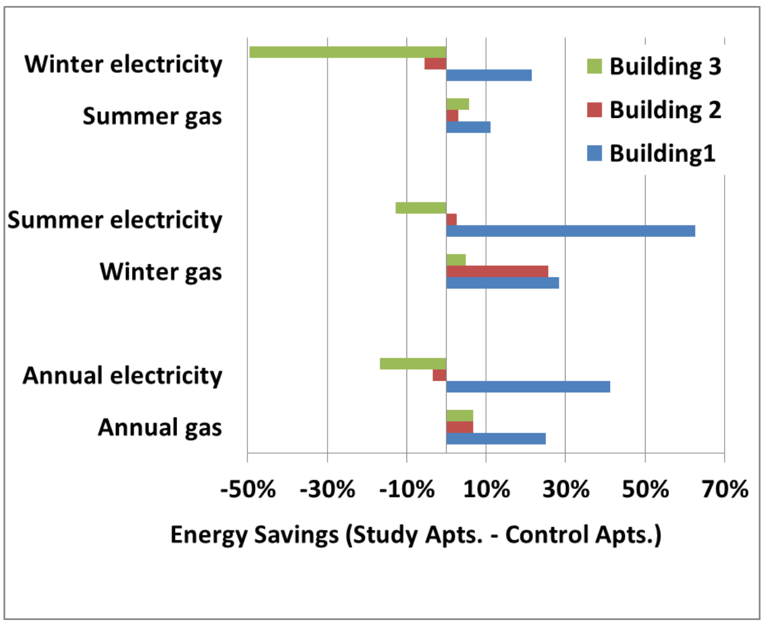
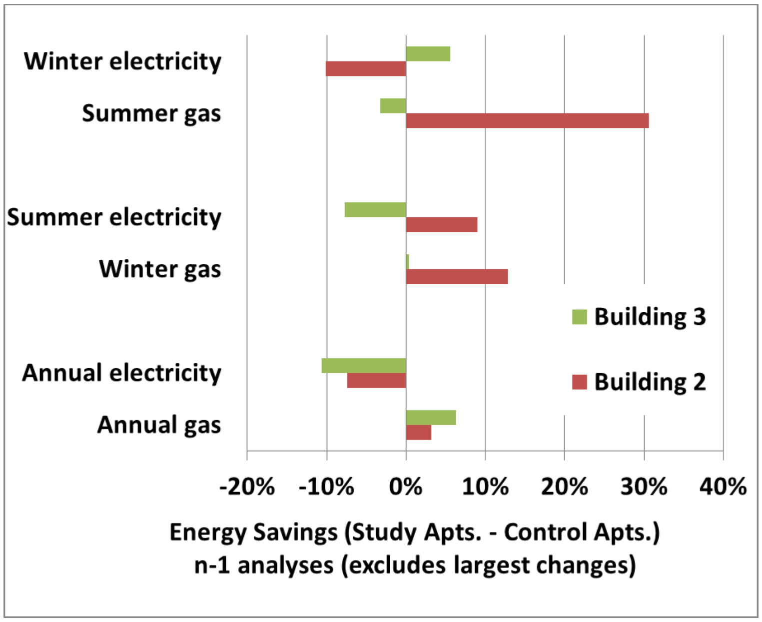


Figure 19 shows the alternate estimate of energy savings for B2 and B2 obtained via the “n-1” analysis. The data continue to indicate small annual gas energy savings and small annual increases in electricity use; however, some of the seasonal results have changed dramatically. In place of the 49% increase in winter electricity use in B3, the “n-1” analysis, which excluded data from one study apartment and one control apartment, indicates a 6% savings. Also, the 3% summer gas energy savings for B2 in Figure 18 becomes a 31% savings in the “n-1” analysis. These large changes indicate that the study size is clearly too small to yield accurate estimates of average energy savings from the retrofits.

Figure 19: Estimated energy savings in B2 and B3 via the "n-1" analysis that excludes data from outliers



When gas energy and electricity site energy are combined, the data indicate annual savings of 28% in B1, 5% in B2, and 3% in B3. These savings are again based on of energy use changes in study apartments minus energy use changes in control apartments. The predicted energy savings were 21%, 17%, and 27% for B1-B3, respectively (Noris, Delp et al. 2013). Only in B1 are the measured savings comparable to the predictions.

CHAPTER 4: Discussion

4.1 Retrofit selection

The retrofit selection protocol developed for this project has several strengths and some limitations. It provides a rational and repeatable method for evaluating candidate retrofits based on energy savings, IEQ benefits, and costs, addressed in an integrated manner. The protocol uses a simple summary metric (cost-normalized benefit score) to compare retrofit options and provides a relatively simple process for calculating these scores. Compared to pre-existing protocols that consider only energy and measure costs, this new protocol provides a better means of maximizing total benefit per unit expenditure. However, there are limitations in methods for quantifying some of the benefits and converting benefits into scores. The protocol would benefit from an accounting for the life expectancy of pre-existing devices (e.g., furnace systems) and the expected life of the retrofits considered. A user-friendly web-based interface would make the protocol more accessible and enable use of a finer-scaled scoring system without imposing burdensome calculations (the current system has only 3 levels, 1, 2, or 3). Additionally, there is substantial subjectivity inherent in the benefit evaluations and in the establishment of the brackets for assigning scores. Ideally, this subjectivity would be reduced; however, to maximize protocol utility, there must be a compromise between accuracy of impact quantification and time and expertise requirements. The presented retrofit selection protocol is a first step in the correct direction.

During the retrofit implementation, the challenging nature of the retrofit work became evident. Available retrofit options were sometimes non-ideal or prohibitively expensive. Conditions identified during the early stages of retrofit implementation sometimes made it necessary to modify plans, and increase retrofit costs. A particular challenge for this project, and possibly for projects in other apartment buildings, was the number of participants. The sometimes divergent motivations and priorities of the various stakeholders – including the building owner, building manager, contractors, tenants, and commissioning agents (in this case, the study team) – make the process challenging and called for extensive communication between the different parties. It is particularly important for contractors to anticipate potential challenges and to communicate with the customer about unforeseen challenges that arise. Likewise, it is important for a qualified party to inspect and evaluate the retrofit work to ensure that specifications were met. In this study, despite use of contractors accredited by the Building Performance Institute some measures were not initially implemented as specified.

The diagnostic measurements made before and after the retrofits and summarized in this document indicate significant improvements in apartment performance. Occupant self-reports of satisfaction with the retrofits were also encouraging. Substantial variations were observed in the level of improvement depending mainly on the initial conditions.

4.2 Changes in IEQ

The findings presented in this paper indicate an overall improvement in IEQ conditions after the retrofits were implemented. In general, the measurements indicate improvements in comfort conditions, bathroom humidity, and concentrations of carbon dioxide, acetaldehyde, VOCs, and PM2.5. However, not all IEQ parameters were improved after the retrofits. Formaldehyde levels decreased in B1, which had the highest concentrations, were essentially unchanged in B2, and increased in B3. The average NO_2 concentration (after adjustment) was essentially unchanged in B2. In B3, NO_2 concentrations were very low and the measurements indicate a large percentage increase in the average concentration after the retrofits, but this finding is uncertain because of the estimated measurement uncertainty at low concentrations. For IEQ parameters other than PM2.5, IEQ improved more in apartments with continuous balanced mechanical ventilation systems installed compared to apartments without continuous mechanical ventilation. In general, larger percent increases in ventilation rates were associated with larger percent decreases in indoor levels of the pollutants that primarily come from indoor sources.

The substantial increase in average formaldehyde concentrations in B3 were unexpected given that the average air exchange rate increased by 60%. The largest percent increases occurred in apartments with quite low pre-retrofit formaldehyde concentrations. Also, formaldehyde concentrations increased marginally in some B2 apartments. The increases could not be linked to any retrofit. Emission rates of formaldehyde from manufactured wood products increase with temperature and humidity. Changes in indoor temperature and humidity were modest and do not appear to explain the increases in indoor formaldehyde levels. Outdoor temperature and humidity were significantly higher after the retrofits in B3 and might have influenced emission rates from formaldehyde sources in walls and attics. Solar heating of wall cavities and attics could have affected formaldehyde emission rates. The introduction of new formaldehyde sources, such as new furniture, by the occupants between the pre- and post-retrofit measurement periods cannot be ruled out, but this seems unlikely in multiple apartments. The ideal approach for reducing these formaldehyde levels would be to identify and remove major sources, although increased ventilation rates may be the only practical option.

The study team is aware of no other study that has evaluated broad packages of retrofits designed to both save energy and improve IEQ conditions, thus, a comparison of the results of this study to prior findings is not possible. Strengths of this study include incorporation of a broad set of high quality IEQ measurements and the reliance on pre- and post-retrofit measurements within apartments, as opposed to use of a cross sectional study design. Study limitations include the moderate number of apartments retrofit. Also, measurements occurred for only two weeks before and after retrofits, and given these limited periods, variability in occupant activities likely affected study results. The study methods cannot control perfectly for changes in outdoor air weather conditions and air pollutant levels. The effects of climate, season, outdoor air quality, and building features cannot be separately determined because of the small number of study buildings.

The generally positive IEQ results reported in this paper should not be assumed to be applicable to the usual energy efficiency retrofits of apartments or single-family homes. In most energy retrofits, there is little or no consideration of IEQ effects when the retrofits are selected. The study results do indicate the potential to improve IEQ during energy efficiency retrofits if retrofit selection protocols are revised so that both energy savings and IEQ are considered.

4.3 Changes in Energy Consumption

The retrofits implemented in this study are widely believed to reduce energy consumption. Predicted energy savings were 21%, 17%, and 29% for B1 – B3, respectively, while measured energy savings were 28%, 5%, and 3%. Hypothetical explanations for the large discrepancy between predicted savings and findings from B2 and B3 are listed below and discussed in the following paragraphs:

H1. The selected retrofits, contrary to general belief, are ineffective in reducing energy consumption.

H2. Retrofit measures included to improve IEQ increased energy use and counteracted the energy savings of other measures.

H3. Changes in apartment use and occupant behaviors obscured the anticipated energy savings.

Relative to the first hypothesis, the evidence of energy savings in B1, but not in B2 and B3, might be partially explained by differences in the retrofits implemented. In B1, the packaged rooftop heating and cooling systems and the water heaters were replaced with new more energy efficient units. Also, gas stoves with standing pilot lights were replaced. Analogous retrofits were not implemented in B2 and B3. Envelope sealing, attic insulation, and window or sliding glass door replacements were implemented in B2 and B3, but not in B1. Average spending on retrofits was higher in B1 ($12,700 per apartment) than in B2 ($7700 per apartment) or B3 ($9000) per apartment. An analysis of the national weatherization program found that attic insulation, insulating water heaters, installing low flow showerheads, and replacing inefficient heating systems were among the most effective energy savings measures (Brown and Berry 1995). Installation of storm windows and doors was less effective (Brown and Berry 1995). Overall; however, sufficient prior data are available from much larger studies to reject the hypothesis that these energy efficiency measures are ineffective. An analysis of measured data from retrofits of over 25,000 housing units (Goldman, Greely et al. 1988) from multifamily dwellings indicated energy savings of 14% to 16%, although these retrofits took place prior to 1988 when savings opportunities were likely larger. A much more recent study of retrofits of more than 21,000 housing units in 231 properties in New York City reported a 19% reduction in fuel energy and 7% reduction in electricity (Steven Winters Associates and H&R Advisors 2012). In the milder California climate, smaller absolute magnitude but similar percentage savings would be anticipated. An analysis, published in 1995, of measured data from the National Weatherization Assistance Program, which targets single family and multi-family homes of low income persons, indicated a 13.5% reduction in total energy use (Brown and Berry 1995). A subsequent meta-analysis of 17 state-level evaluations of the National Weatherization Assistance Program indicates a 23% reduction in natural gas use in gas-heated homes (Berry, Brown et al. 1997). Each of these larger programs that reported energy savings employed retrofit measures that overlap highly with the retrofits in the present study. Thus, one can conclude that, on average, these retrofits save energy.

With respect to hypothesis 2, it is clear that that some of the retrofits included in the study to improve IEQ lead to energy consumption; however, the amount of energy consumed is moderate. The 23 W fans in the energy recovery ventilators installed in B1 apartments and in three apartments in B3 are projected to consume 0.55 kWh per day, if operated continuously. The automatic intermittent operation of bathrooms fans in apartments are projected to consume a negligible 0.01 kWh per day if operation is triggered 10 times per day with 20 minute operation periods. The exhaust fans operating continuously in three B3 apartments consume a projected 0.1 kWh per day. The wall-mounted air cleaners installed in B2 and B3, were projected to consume 0.22 kWh per day, assuming they were run in the automatic mode (as recommended) which employs a low fan speed most of the time (assumed 70% of time) and higher fan speeds when elevated indoor concentrations of particles are detected. Together, the added fans consume about 3% and 2.4% of total average pre-retrofit electricity consumption of B1 and B2 apartments, respectively. In the three B3 apartments with energy recovery ventilators and air cleaners, the added fans are projected to consume 5.7% of average pre-retrofit electricity. In the remaining three B3 apartments, with continuously operating bath fans and air cleaners, the added fans are projected to consume 2.4% of average pre-retrofit electricity. These calculations assume no change in range hood fan energy, as the data indicated no increase in range hood use after retrofits.

The effects of envelope sealing plus operation of continuous mechanical ventilation systems (installed in B1 and B3 apartments) on space conditioning (heating and cooling) energy use are less readily estimated. The B1 apartments and three of the B3 apartments had energy recovery ventilators installed, with significant envelope sealing only in B3. The manufacturer reports 66% and 33% sensible and latent energy recovery by the energy recovery ventilator. The remaining three B3 apartments had envelope sealing and continuously-operating exhaust fans installed. Modeling of single family homes indicates that envelope sealing plus continuous mechanical ventilation at a rate sufficient to meet the requirements of ASHRAE Standard 62.2 (ASHRAE 2010) will decrease space conditioning energy consumption, particularly when the mechanical ventilation system includes energy recovery (Walker and Sherman 2008). There are key differences between the modeled scenario and actual study. First, in the present study there was no significant envelope sealing in the B1 apartments, thus, the mechanical ventilation in B1 must have increased space conditioning energy use. However, the data from the B1 apartments still suggests energy savings. Second, sealing of envelopes in apartments may be less effective in reducing infiltration from outdoors than sealing envelopes in single family homes. Third, the mechanical ventilation rates in the present study were 150% of the rates prescribed in the ASHRAE Standard. However, in apartments much of the “ventilation” air comes from surrounding apartments, and these surrounding apartments are typically heated or cooled. Thus, the amount by which the mechanical ventilation systems increased ventilation from outdoors, imposing heating or cooling loads, may not have been larger than prescribed in ASHRAE Standard 62.2. The seasonal trends in changes in energy use suggest that space conditioning loads caused by mechanical ventilation do not explain the lack of energy savings. The data indicate savings in B1 despite continuous mechanical ventilation of all B1 apartments and no apartment envelope sealing. There was no continuous mechanical ventilation in B2, and still the measured energy savings were small. In B3, full year and winter time gas energy consumption decreased by a similar small amount. Also, full year electricity use in B3 apartments increased by more than summer electricity use, suggesting that ventilation-caused mechanical ventilation was not a major cause of the increase in electricity use in B3.

Considering the information provided in the prior two paragraphs, the energy consumption of IEQ improvement measures appears insufficient to explain more than a modest portion of the large discrepancy between predicted and measured energy savings in B2 and B3. However, uncertainties remain with respect to the effects of mechanical ventilation in B1 and B3 on apartment energy use.

The study data are consistent with hypothesis 3. The large variability in pre-retrofit energy use in apartments within the same building (Table 4), the large, both positive and negative, changes in energy use within control apartments (Table 5), and evidence that climate was not the major driver for variability in energy use (Figure 16), all suggest that changes in occupants' behaviors strongly affected energy use. These findings plus a comparison of results of the "n-1" analysis to results of the primary analysis all indicate that the present study was too small to provide a reliable measurement of the effects of the retrofits on energy consumption. There is an increasing appreciation of the large effects of occupant behaviors on building energy consumption (Lutzenhiser 1993, Haas, Auer et al. 1998). Also, there is a recognized take-back or rebound effect, in which people use more energy, e.g., via increased space heating and cooling, after energy efficiency retrofits (Hertwich 2005). Finally, in these apartments, the number of occupants may have varied significantly over time and, as shown in Figure 16, occupancy was a fairly strong predictor of apartment energy use.

Relative to hypothesis 3, the large changes in winter electricity use in apartments B3A5 and B3A1c are notable. In study apartment B3A5, post retrofit winter electricity was 79% higher than pre-retrofit winter electricity use. Changes in this magnitude might be explained by use of electric space heating only in the post-retrofit year; however, at the start of the study tenants reported not having an electric space heater. Also, the increase in winter electricity use was accompanied by a simultaneous 27% increase in winter gas use; thus, electrical heat was not obviously substituting for gas heat. In control apartment B3A1c, winter electricity use was 69% lower in the post retrofit year while winter gas use increased 21%, suggesting the possibility that electrical space heating in the pre-retrofit period was partially replaced by gas heating in the post-retrofit period. However, the tenants of B3A1c also reported not having an electric space heater. The reasons for the large changes in winter electricity use of these two apartments are unknown.

Key strengths of the energy aspects of this study include the reliance on a full year of pre-retrofit and post-retrofit measured energy data. Many studies have simply predicted energy savings. Also, the inclusion of numerous similar control apartments from the same apartment buildings represents a study strength. The main study weakness is the small number of apartments. The study size was cost constrained.

4.5 Research needs

This project was the first known broad investigation of the potential to implement packages of retrofits in apartments that simultaneously save energy and improve IEQ conditions. A replication of the study, while retrofitting a larger set of apartments, is desirable. With a larger set of apartments, average study results would be less affected by random changes in IEQ conditions and energy consumption driven by changes in occupant behaviors.

Research is also needed to further develop the retrofit selection protocol to account for the expected life of existing apartment equipment and the availability of rebates or incentives for retrofit measures. Also, a user friendly web-based interface would make the protocol much easier to utilize and would make it practical to employ a finer scale for the retrofit scores.

Finally, it would be beneficial to have versions of the retrofit selection protocol for apartments that have HVAC systems shared with other apartments and for single family homes.

CHAPTER 5: Conclusions

1. There are opportunities to simultaneously save energy and improve IEQ when apartments are retrofit; however, IEQ is normally not considered at the time of retrofit selection.

2. This study developed a protocol for selecting retrofits based on predicted energy use and IEQ changes, retrofit cost, and initial apartment conditions. Relative to current practices, the protocol described in this document has the potential to better capitalize on the total societal benefits of building retrofits, consequently, the protocol should be of interest to building owners, retrofit contractors, utilities, and governmental organizations involved with building retrofits.

3. In the apartments within this study, diagnostic measurements identified frequent low air flow rates in existing bathroom fans and kitchen range hoods, as well as bathroom fans and range hoods with no exhausts to outdoors or obstructed exhaust ducts. Other common deficiencies included old inefficient heating and cooling systems and refrigerators, leaky ducts and building envelopes, pilot ignition gas stoves, single pane windows and glass doors, minimal attic insulation, and incandescent light bulbs.

4. A challenge identified with retrofits that incorporate exhaust ventilation was the risk of combustion pollutant backdrafting from natural draft water heaters coupled with the limited availability of quiet forced-combustion water heaters.

5. The results of this study indicate the potential for overall improvements in IEQ when a package of retrofit measures is implemented in apartments to both save energy and improve IEQ. There was a general improvement in comfort conditions, bathroom humidity, and concentrations of carbon dioxide, acetaldehyde, VOCs, and PM2.5. However, not all findings were positive. Formaldehyde levels decreased in B1, which had the highest concentrations, were unchanged in B2 and increased in B3. Also, NO_2 levels decreased in B1, which had the highest concentrations, were unchanged in B2, and increased in B3 which had the lowest concentrations. The increases in NO_2 in apartments within B3, although large as a percentage, have a small absolute value because the initial concentrations were very low. Thus, the increases are not particularly significant and are also uncertain because of the uncertainties associated with measuring very low concentrations. For IEQ parameters other than PM2.5, IEQ improved more in apartments with continuous mechanical ventilation systems installed compared to

apartments without continuous mechanical ventilation. Indoor concentrations of PM2.5 decreased more when the retrofits included installation of wall-mounted air cleaners. In general, but not consistently, larger percent increases in air exchange rates were associated with larger percent decreases in indoor levels of the pollutants that primarily come from indoor sources.

6. Analyses of pre- and post-retrofit energy data from apartments receiving energy retrofits and from control apartments suggest small energy savings, driven by reductions in natural gas use. Because of the small number of retrofit apartments, the data provide no conclusive evidence of retrofit-caused energy savings. Much larger studies employing similar retrofits have shown that the retrofits usually save energy.

7. Apartment energy use increased with number of occupants. The associations of apartment energy use with apartment floor area and with number of external envelope surfaces were weak.

8. There were large and variable year-to-year changes in energy use in control apartments, potentially caused, in part, by changes in occupant behavior and occupancy. Given that magnitude of these natural changes in apartment energy use, the present study was too small to measure the energy impacts of the retrofits on energy consumption.

9. The study included mechanical ventilation and particle filtration retrofits, designed to improve IEQ and some of these measures increased energy consumption. Although uncertainty remains, the energy consumption of the IEQ-improvement measures appears insufficient to explain why the measured energy savings in B2 and B3 are far smaller than the predicted savings.

GLOSSARY

Term	Definition
ACH_{50}	Air changes per hour at 50 Pascals
AHU	Air handling unit
B1	Building 1
B2	Building 2
B3	Building 3
BmAn	Building number m, apartment number n
BmAnc	Building number m, apartment number n, control apartment
BPI	Building Performance Institute
CAZ	Combustion appliance zone
CDD	Cooling degree days
CO	Carbon monoxide
CO_2	Carbon dioxide
DNPH	2,4-dinitrophenylhydrazine
Elec.	Electricity
EPA	Environmental Protection Agency
ERV	Energy recovery ventilator
Ex.Vent,	Intermittent exhaust ventilation.
GC-MS	Gas chromatography mass spectrometry
HDD	Heating degree day
HES	Home energy saver web based program
HVI	Home Ventilating Institute
HPLC	High performance liquid chromatography
HVAC	Heating, ventilating, and air conditioning
IAQ	Indoor air quality
IEQ	Indoor environmental quality
MERV	Minimum efficiency reporting values (a measure of filter efficiency)
NL_4	Normalized leakage at 4 Pascal
NO_2	Nitrogen dioxide
PFT	Per fluorocarbon tracer
PM2.5	Mass concentration of particles less than 2.5 microns in diameter
REL	Reference exposure level
RH	Relative humidity
T	Temperature
VOC	Volatile organic compound

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APPENDIX A1:
Tenant Indoor Environmental Quality and Energy Education

In addition to the physical retrofits, the interventions included tenant education about maintaining indoor air quality (IAQ), energy efficiency and comfort in the apartments. After the physical retrofits were implemented, a member of the project staff visited the apartment and: 1) provided tenants a copy of the HUD Healthy Homes booklet for general education on IAQ and point out sections of key interest, 2) verbally informed tenants about use and maintenance of the retrofits implemented in their apartment, 3) provided tenants with a one-page document with tips for maintaining apartment energy efficiency.

A copy of the HUD Healthy Homes booklet that was given to tenants for general education about maintaining good IAQ is available at http://www.hud.gov/offices/lead/library/hhi/HYHH_Booklet.pdf

The verbal education about use and maintenance of the retrofits covered topics from the following list that apply to the specific apartment.

- Operation of the energy recovery ventilation (ERV) system and periodically vacuuming its two filters with a soft brush attachment.
- Use of the bathroom exhaust fans when showering.
- Use of the kitchen exhaust fan/hood when cooking to remove pollutants.
- Installing the cover on window air conditioner (AC) during the winter to reduce the exfiltration of conditioned air and drafty conditions; removing the covert during the summer months when the AC is used.
- Operating and programming the programmable thermostat.
- Operating efficiently the air conditioning and/or heating system.
- Replacing periodically the filters in the heating and air conditioning system.
- Using portable fans instead of air conditioners to reduce the energy bills

The following IEQ tips were communicated:

- Ventilation is key to controlling indoor air pollutants. Using the ERV will provide good ventilation to your apartment. In mild weather, when you are not heating or cooling, open windows. Please turn off ERV when barbequing in the patio. The ERV filters need to be cleaned (vacuumed) every 3 months.
- Dampness and mold in buildings causes respiratory health effects. To help prevent dampness and mold, operate your bathroom fan when bathing and your range hood when cooking. Don't hang wet clothes indoors unless windows are open, particularly when it cold. If there are any water leaks, notify maintenance

staff. If a small amount of mold develops in your bathroom, clean it up with dish soap and a rag or soft brush.

- Cooking produces many invisible air pollutants. Operating your new vented range hood during cooking is necessary to reduce indoor pollutants from cooking. The range hood works best when you cook on back burners.
- Avoid unnecessary sources or air pollutants such as indoor tobacco smoking, air fresheners, and candles.
- If you have cockroaches or ants, use roach or ant traps, and minimize spraying of pesticides. Mice and rats can be sources of allergens. If your apartment has mice or rats, notify apartment maintenance staff. Dust mites in bedding are a source of allergens. Clean your bedding regularly in hot water and dry it in a hot clothes dryer. Keep your house clean and free of food scraps or crumbs that can attract pests. Vacuum regularly to minimize dust.

Also, the occupants were given the following one-page document with tips on no-cost energy savings. The content was drawn from documents developed by utilities, and a state energy office:

No Cost Energy Savings Tips for Tenants

1. Turn off equipment and appliances – such as lights, televisions, stereos, DVD players and computers when you are not using them.

2. Wash and dry full loads. This reduces the number of loads and saves energy. Do only full loads when using your clothes washer and dryer. Also, for most situations wash in cold water which usually does a good job of cleaning your clothes. If needed, wash with warm water. You can always use the cold rinse cycle.

3. Wash only full loads in your dishwasher.

4. If you have a leaky faucet, ask your apartment manager or maintenance staff to fix it.

5. During winter:

- For each 1 degree Fahrenheit that you lower your thermostat setting, you can save 2% to 3% percent of the energy that your furnace uses.
- Open window coverings on sunny days to let the sun help heat your house. Close the window coverings when cloudy and at night to help keep heat in the house.

6. During summer:
   - If you use air conditioning, for each 1 degree Fahrenheit that you increase your thermostat setting you will save 3% to 5% of the energy used by your air conditioner.
   - On hot days, keep windows closed during the hottest part of the day and close window shades to reduce the rate at which heat from the sun enters you apartment. During early morning and at night, if it is cool outdoors, open windows and turn off the air conditioner if you have one.
   - Use a fan to create air motion over your body so that you can stay comfortable with a higher indoor temperature. However, elderly people should not use fans when the indoor temperature exceeds 100 degrees Fahrenheit.

APPENDIX A2:
Retrofit Selection Protocol

A2.1 Purpose of This Appendix

This document defines the retrofit selection strategy employed for the research project entitled "Energy and Indoor Environmental Quality (IEQ) Retrofits in Low-Income Apartments." This document identifies the retrofit actions considered, the parameters involved in the analyses, how benefits of retrofits were estimated, and how cost normalized benefit scores were calculated.

A2.2 Context

This project developed protocols for selecting packages of retrofits intended to both reduce energy use and improve indoor environmental quality (e.g., indoor air quality, comfort) in California apartments with low-income occupants. The project retrofitted 16 total apartments from three buildings, and utilized measurements in the retrofitted apartments and in un-retrofitted control apartments to assess the energy savings and indoor environmental quality changes.

Retrofits of existing apartments in multifamily apartment buildings can impact the apartment's energy consumption and aspects of indoor environmental quality (IEQ) with consequences for energy performance, comfort, and health. The goal of this retrofit selection protocol was to provide a rational and repeatable method for selecting retrofit packages that improve apartment performance and living condition within budget constraints. Ideally, the retrofit selection strategy would be able to maximize the total benefits with respect to the investment. Given the many uncertainties and the practical data collection and analysis constraints, one can only expect that the retrofit selection protocol will yield a first-order approximation of the optimal package of retrofits. This protocol can be considered as a first step toward a comprehensive quantitative selection tool that agencies and stakeholders involved in the retrofit industry could utilize to optimize the use of the resources.

A2.3 Overall Retrofit Selection Methodology

We identified retrofit actions most appropriate for the apartment. Subsequently, this list of retrofits was modified to address building owner and tenant inputs and approval. The recommended list of retrofits selected included a group of "a-priori" measures that are recommended for adoption whenever applicable, without analyses or scoring. The a-priori measures are retrofits needed to meet minimum ventilation standards or address combustion safety concerns, or are measures with low costs and well-established benefits. Another group of retrofits was selected using a semi-quantitative analysis and ranking procedure to estimate the total benefits of the retrofit normalized by the anticipated installed cost of the retrofit.

The list of a-priori retrofits includes:

1. Air sealing. Seal interior walls to reduce the entry of pollutants from other apartments and common areas of the building. Also, seal exterior walls in apartments for which continuous mechanical ventilation is installed.
2. Mechanical ventilation. Given the importance of outdoor air ventilation for controlling indoor concentrations of a variety of contaminants and the moderate energy cost of ventilation in the California climates of interest, we targeted exceeding the ASHRAE 62.2-2007 ventilation requirements (ASHRAE 2007), unless prohibited by excessive retrofit cost or by owner/tenant reluctance. This retrofits included:
    a. Continuous mechanical ventilation: Upgrade or install mechanical ventilation equipment to provide 150% of the mechanical ventilation rate required by Equation 4.1b of the ASHRAE 62.2-2007 Standard (ASHRAE 2007). This goal was achieved with a balanced energy recovery ventilation (ERV) system or with a continuously-operating bathroom exhaust fan. Equation 4.1b in Standard 62.2 includes a default infiltration credit of 2 cfm/100 $ft^2$of apartment floor area. We recognize that in some apartments all infiltration air could enter from other apartments; however, by adopting a goal of 150% of the minimum mechanical ventilation rate in the ASHRAE standard (calculated with Equation 4.1b) we are more likely to maintain adequate ventilation even in apartments without infiltration from outdoors.
    b. Local ventilation in kitchen and bathroom(s): Upgrade or install a new kitchen exhaust (ideally a range hood) and bathroom exhausts vented to outdoors, using systems that meet ASHRAE Standard 62.2 requirements. Bathroom exhaust systems may operate intermittently or operate continuously.
3. Improve HVAC system filtration. In apartments with forced-air heating, ventilation and/or air-conditioning (HVAC) systems incorporating particle filters, when feasible, minimize filter bypass and upgrade the current filtration level by installing a filter with minimum efficiency reporting value (MERV) as determined by ASHRAE

Standard 52.2 of 9 to 13 (ideally 11-12) based on the findings reported by (Fisk, Faulkner et al. 2002)). [1]

4. Water heater system. In apartments with individual water heaters, install low flow showerheads, and add insulation to water tank (jacket) and water lines after checking for obstructions in air supply and stack.

After identifying retrofits from this first group, the remaining budget per apartment was then used to select retrofit actions based on a scoring and ranking process. We estimated the potential impacts of each retrofit in three categories: energy, indoor air quality (IAQ), comfort. Each retrofit received a benefit score on a -3/+3 scale (-3 = large negative impact, -2 = moderate negative impact, -1 = slight negative impact, 0 = no impact, 1 = slight positive impact; 2 = moderate positive impact; 3 = large positive impact) for each of the impact categories considered and the scores were summed to obtain a total benefit score for the retrofit. The assignment of benefit scores was based on engineering judgment supported, when practical, by calculated estimates of energy or IAQ impacts. Finally, the total benefit score was divided by the expected cost of the retrofit to estimate the cost normalized benefit with respect to the investment. The candidate retrofits were then ranked based on their total normalized benefit (total score/estimated cost) and the highest ranked retrofits were selected until the retrofit budget was expended. Subsequently, the proposed retrofits were discussed and negotiated with the building owner and tenants in order to finalize a package of approved retrofits.

Energy benefits were evaluated in most cases using the web based Home Energy Saver – HES – tool (http://hes.lbl.gov). The tool, considering the initial condition of a residence, suggests retrofit actions to improve the energy efficiency as well as estimates costs of the retrofits, yearly savings and payback times for different improvement options. For this evaluation we utilized the townhouse option using a high level of attic insulation if there was an apartment above the one in question.

We estimated the potential IAQ benefits of some retrofits with simple mass-balance models using data from measurements and values obtained from the literature as input. This approach, even with its limitations and assumptions, yielded predictions of the impacts of retrofits in reducing concentrations of harmful contaminants, providing an improved basis for assigning benefit scores.

For some retrofits, published empirical data were used to estimate the impact of the retrofit on the predicted percentage dissatisfied (PPD) with thermal comfort. For the purpose of this document, the noise perception and the loudness of the equipment was included in the comfort category.

[1] Also a simple model simulation for typical conditions revealed that increasing the filtration level from a MERV <5 to a MERV 11 filter could reduce indoor particles less than 2.5 micrometers by approximately a fourth.

Figure A2.1 illustrates the schematic of the overall process. A list of potential candidate retrofits was compiled based on suggestions from project consultants and advisory committee members. Initial information on buildings and apartments was collected via phone-based interview with building manager (Section A2.4). Subsequently, the tenants interested in participating identified themselves. The information collected during the manager's interview was supplemented by information gathered from on-site inspections using defined protocols (sections A2.5 and A2.6). Additionally, selected measurements were performed to collect critical data (section A2.7). With the information collected during the interview, inspections, and measurements, the impacts of the retrofits were estimated in the three categories. Section A2.8 presents the models utilized for estimating the impact of some retrofits on IAQ, while Section A2.9 provides instructions for using the HES website as part of the retrofit selection protocol. Table A2.1 lists the candidate retrofits with the corresponding impact categories likely to be affected.

Subsequently, after retrofit scores were assigned and normalized with respect to their estimated cost, a ranked list of proposed retrofits was developed. Section A2.10 explains how the retrofit costs were estimated for the retrofits not included in HES, while section A2.11 specifies the strategy for assigning benefit scores and how to develop the retrofit ranking. After the preferred retrofits were identified, they were discussed with the owner and tenants to assess their willingness to have the retrofits implemented, yielding a final retrofit package for each apartment.

Figure A2.1: Schematic of the overall process

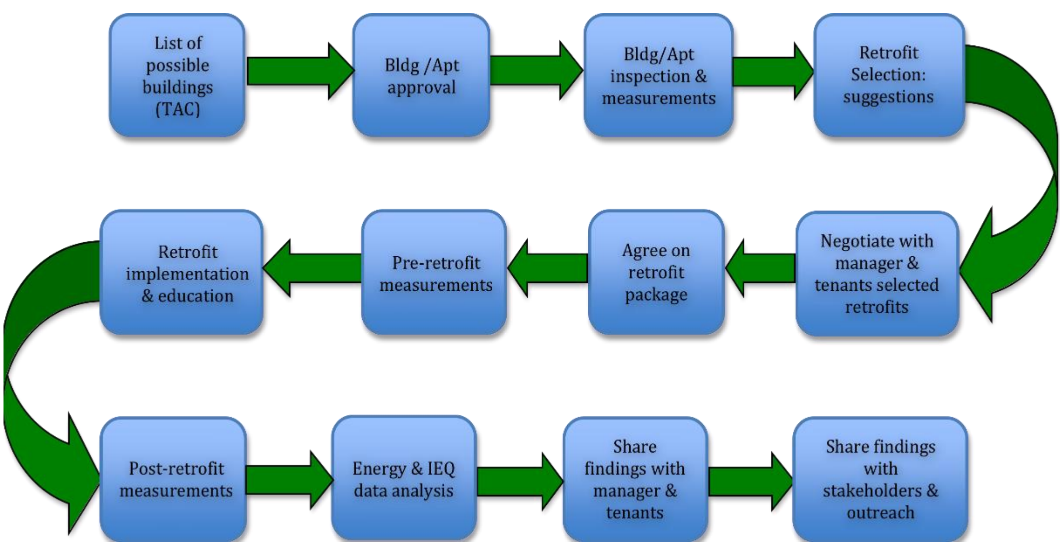

Table A2.1: List of potential retrofits with categories likely to be impacted by the action.

Retrofit		Categories impacted
Ventilation		
Seal interior connections between apartment and remainder of building[1]		IAQ, energy, comfort
Seal external walls, floors, ceiling[2]		IAQ, energy, comfort
Install balanced heat recovery ventilation (HRV) [3]		IAQ, energy, comfort
Install continuously operating vented bathroom exhaust fan[3]		IAQ, energy
Replace continuously operating bathroom exhaust fan because[3]:	Noisy	Comfort
	Low flow	IAQ
Install intermittently-operating (e.g. timer controlled, humidity sensing, occupant sensing) vented bathroom fan[3]		IAQ, energy
Replace intermittently-operating (e.g. timer controlled or humidity sensing or occupant sensing) vented bath fan for source control only because[3]:	Noisy	Comfort
	Low flow	IAQ
Install vented kitchen exhaust system (ideally a range hood)[3]		IAQ, energy
Replace existing vented kitchen range hood because[3]	Inefficient	Energy
	Noisy	Comfort
Install cover on window air conditioners		Energy, comfort
Thermal Comfort / Heating & Cooling		
Add external wall insulation		Energy, comfort
Add ceiling insulation in top-floor apartments		Energy, comfort
Install programmable thermostat		Energy, comfort
Replace or repair air conditioner because:	Inefficient	Energy
	Noisy	Comfort
	Water leak	IAQ
Replace or repair heating device because:	Inefficient	Energy
	Noisy	Comfort
	Polluting	IAQ

Table A2.1: (continued)

Retrofit		Categories impacted
Thermal Comfort / Heating & Cooling		
Ensure adequate air supply for all combustion appliances, eplace unvented heating device with a sealed vented one		IAQ, energy
Seal and insulate HVAC ducts in unconditioned space and cavities		Energy
Improve HVAC filtration[1]		IAQ
Add air-moving device (fan):	With AC	Energy
	Without AC	Comfort
Replace broken windows		Energy, comfort
Upgrade existing windows		Energy, comfort
Add window film or shading		Energy, comfort
Source Control		
Fix leaking water pipes causing water damage		IAQ
Water seal in bath and/or kitchen		IAQ
Moisture and mold retrofits (budget limited to < $2K)		IAQ
Replace pilot ignition combustion appliances (gas stove, furnace) with comparable or more efficient units with electronic ignition		IAQ, energy
Replace combustion appliance (furnace, water heater) with potential back drafting with fan powered appliance		IAQ, energy
Replace combustion appliance (furnace, water heater) with faulty vent		IAQ, energy
Vent existing clothes dryer to outdoors		IAQ
Install CO monitor		IAQ
Appliances		
Replace inefficient water heater with a more efficient one		Energy
Energy efficient lighting upgrade (e.g., CFLs)		Energy
Replace inefficient refrigerator or dishwasher		Energy
Upgrade water heating system (i.e., install low flow showerhead, add insulation) [1]		Energy

[1] A-priori action

[2] A-priori action unless we cannot provide mechanical ventilation

[3] Alternative a-priori actions to meet whole-unit and local exhaust ventilation requirements

Due to financial constraints, the study focused on retrofits of apartments, not retrofits of apartment buildings. Consequently, apartments served by centralized heating and cooling systems that serve multiple apartments were not included in the project.

Some desirable retrofits were excluded because of cost constraints (limited retrofit budgets) or to avoid liabilities. Retrofits that would disturb asbestos containing materials were excluded. Apartments with severe moisture and mold problems were to be excluded from the study, although none were encountered.

In addition to physical retrofits, which are changes in components and devices of the apartment, the intervention included education of manager and tenants about maintaining the IEQ, energy efficiency, and comfort of their apartment. This education provided basic information about how tenant actions may affect energy use and IEQ, and a description of the physical retrofits and how to use them. We used a combination of already available educational materials (i.e., HUD healthy homes brochure and EPA Indoor airPLUS brochure) and educational material produced for this project that will address the specific retrofits implemented in the apartments (e.g., replacement of HVAC filters, use of kitchen and bath exhausts, thermostat setting). This educational element was expected to be critical for maximizing the benefits of the retrofits.

The subsequent sections of text provide the following additional documentation needed to implement the retrofit selection protocol.

- Section A2.4 is the building screening protocol with a list of questions to be utilized in the interview of the building manager. The information collected was used to verify if the building was a suitable candidate for the investigation and to decide which retrofits to select.

- Section A2.5 is the building inspection protocol and data collection sheet. The information gathered was used to select the retrofits.

- Section A2.6 is the apartment inspection protocol and data collection sheet. The information gathered was used to select the retrofits.

- Section A2.7 describes the measurements implemented as part of the diagnostic assessment process. The protocols for implementing these measurements and the data collection forms are also provided.

- Section A2.8 provides instructions for using IAQX software and other models to estimate the impact of retrofits on IAQ.

- Section A2.9 provides instructions for using the Home Energy Saver (HES) web site as part of this retrofit selection protocol.

- Section A2.10 describes the assumed retrofit costs for cases when the HES web site does not estimate costs.

- Section A2.11 describes the procedure for assigning benefit scores and ranking respective retrofits.

A2.4 Building Screening Protocol: Building Owner Interview

Building ID
Code:____

Manager ID
Code:____

Interviewer Name:
____

Date: _______________________________ Time: _______________________

Explain the project and answer general questions, then ask the following questions:

Are you willing to potentially participate in the study? Yes No

Does the building serve low-income population? Yes No

Specify type of project:

When was the building built?

Has building or, to your knowledge, any individual apartments ever received a significant energy efficiency or air quality retrofit? Yes No

Explain:

How many apartments are present in the building?

How many stories above grade does the building have?

How many apartments are currently occupied?

Is this occupancy fraction typical? Yes No

Explain:

Do you think your building has at least 10 apartments with tenants who do not smoke?
Yes No

Do you think that your building has at least 7 apartments with tenants that are likely to participate? Yes No

Do you think they have been in and are likely to stay in the apartments for at least 12 month before and after the retrofits? Yes No

Do most apartments have at least one competent English-speaking adult? Yes No

Is natural gas consumption metered for individual apartments? Yes No

Is electricity consumption metered for individual apartments? Yes No

Does each apartment have an independent heating system? Individual
Central (building) No heating

Are apartments heated with electricity or gas? Electricity Gas

Does each apartment have an independent air conditioning (AC) system? Individual
Shared no AC

Are apartments connected to a central exhaust system (e.g., an exhaust fan on the roof that draws air from multiple apartments)? Yes No Don't know

If yes, do they have backdraft dampers? Yes No Don't know

Does each apartment have an independent water heater? Yes, gas Yes, electricity No (Shared) No water heating

Do apartments have gas or electric stove/cooktops: Gas electric

Are there security measures at building entrance? Yes No
Explain:

Are there security measures at individual apartments? Yes No

Explain:

Based on this information collected the building qualifies/does not qualify to be a candidate for this study.

How many buildings are present at the property?

What is the fraction or family and senior tenants?

Which utility provides electricity?

Is the building served by gas? Yes No

Utility:

What are the typical sizes of the units (ft^2)?

1BR ; 2BR ; 3BR ; 4BR

Is smoking allowed in the building? Yes No

To the best of your knowledge, does smoking regularly occur in units? Yes No

Are there units that you would suggest us to exclude for safety reasons (i.e., illegal activity, uncooperative tenants)? Yes No

Specify:

Do all apartments have same heating and cooling equipment? Yes No

If no, explain:

Are heating costs included in the rent? Yes No

What type of heating system is used?

Electric baseboard Electric furnace Gas Wall Furnace Gas furnace in closet Other:

Do they vent to the outside? Yes No Don't know

Do they have pilot lights? Yes No Don't know

Are they fan-forced? Yes No Don't know

Direct vent (combustion air from outside)? Yes No Don't know

Could you rate the heating systems for providing comfort?

Scale 1-5: 1 = multiple complaints each winter from at least a few tenants; 3 = complaints only in certain apartments (e.g. top or bottom floors) or very sensitive tenants; 5 = almost all tenants satisfied almost all the time.

1 2 3 4 5

Explain:

Are cooling costs included in the rent? Yes No

What type of air conditioner is used? Wall/window Central in closet Other:

Could you rate the cooling system for providing comfort?

Scale 1-5: 1 = multiple complaints each summer from at least a few tenants; 3 = complaints only in certain apts (e.g. top or bottom floors) or very sensitive tenants; 5 = almost all tenants satisfied almost all the time.

1 2 3 4 5

Explain:

Type of construction Masonry Wood-frame Other:

Are external walls of apartments insulated? Yes No Don't know

Type/level:

Are the internal walls of apartments insulated? Yes No Don't know

Type/level:

Which type windows do apartments have? Single-pane Double-pane

Frame: Wood Vinyl Aluminum

Was there any replacement? No (original) Yes, year:

Has any equipment been replaced? Yes No

Heating No Yes How many? When?

Cooling	No	Yes	How many?	When?
Hot water	No	Yes	How many?	When?
Cooking	No	Yes	How many?	When?
Range hood	No	Yes	How many?	When?
Bath exhaust	No	Yes	How many?	When?

Are there any specific apartments that are in most need of upgrades? Yes No

Explain:

Are water heating costs included in the rent? Yes No

Is water heated with gas or electricity? Gas Electric

Do they have pilot lights? Yes No Don't know

Do they have power vents? Yes No Don't know

Direct vent (combustion air from outside)? Yes No Don't know

Do apartments have programmable thermostats? Yes No

Do apartments have gas or electric stove /cooktops: Gas electric

With oven? Yes No

Do they have pilot light? Yes No Don't know

Do kitchens have range hoods? Yes No

If yes, do these hoods vent to outdoors? Yes No Don't know

Do bathrooms have exhaust fans?

If yes, where do they vent? Vent out wall Vent through roof Don't know

Are you aware of the presence of asbestos in the building? Yes No

If yes, describe:

Are you aware of presence of lead-based paint in the building? Yes No

If yes, describe:

On average, how long are most apartments occupied by the same tenants?

< 1 year 1 – 2 years 2-3 years > 3 years

Do apartments have individual clothes washers? Yes No

Do apartments have individual clothes dryers? No Yes-Gas Yes-Elec

How do you (or property management company) typically interact with tenants?

How might you/we inform tenants about this project?

Is there a leadership structure (tenant organization) at the site?

If so, can you describe it?

Are tenants frequently involved in activities at the site?

Have residents ever participated in research studies?

Were these well received?

Any complications?

Notes:

A2.5 Building Inspection Protocol and Data Collection Sheet

Building ID Code: ____

Inspector Name(s): ____

Date: Time: ____

Number of stories:

Building shape:

Building orientation:

Safe conditions in neighborhood and especially in vicinity of building? Yes No

Is a pollution source nearby (within ~300 ft)? None Freeway/busy street Factory Restaurant Dry cleaner

General conditions of exterior, common areas and grounds? Good Fair Poor

What is the type of envelope construction? Masonry Wood-frame Other:

What is the exterior finish material?

Wood siding Aluminum siding Vinyl siding Stucco Brick

Are problems visually evident in the building envelope? Yes No

Describe:

What type of roof? Flat Sloped

Type:

Is there an attached garage below building? Yes No

Appropriate and secure location for outdoor equipment? Yes No

Explain:

Gas and electricity meters for individual apartments? Yes No

Are there internal or external (motel style) corridors? Internal External

Do exhausts from apartments connect to common exhaust shaft? Yes No

Is there an elevator shaft? Yes No

Number of total apartments:

Number of apartments per floor:

Photographs:

Notes:

Sketches of the building:

A2.6 Apartment Inspection Protocol and Data Collection Sheet

Apartment ID Code: ____

Inspector Name(s): ____

Date: ______________________________ Time: ______________________

Criteria

Presence of an individual heating system?	Yes	No
Presence of an individual air conditioning system?	Yes	No
Broad scale moisture and mold problem?	Yes	No
Availability of necessary power for equipment?	Yes	No
Safe conditions for equipment and researchers?	Yes	No
Presence of at least one English (or Spanish) speaking?	Yes	No

Based on this information collected the apartment qualifies/does not qualify to be a candidate for this study.

General

Number of occupants: Adults: Children (0-18):

Story of the apartment:

Location of the apartment on the story:

Size of apartment (ft^2):

Number of sides exposed to outdoors (external walls)

Orientation of apartment entry door (N, S, W, E) from corridor:

Number of bathrooms

Number of baths with shower

Number of bedrooms

Any signs of pest infestation? Yes No

Pest dropping/debris/residue

Pest traps

Pesticide containers

Is there odor in the apartment? Yes No

Location

Possible cause

Ventilation

Is the apartment mechanically ventilated? Yes No

Continuous exhaust-only		Air-handler ducted to outdoors

Is there a working vented bathroom exhaust in bath 1?		Yes		No

Does it have a local fan?		Yes		No

Make:		Model:		Year or SN:

Vent connected to?		Common shaft		Individual duct

If individual, duct exits through:		Roof		External wall

Does the local bathroom fan have backdraft dampers?		Yes		No

Is there a working vented bathroom exhaust in bath 2?		Yes		No

Does it have a local fan?		Yes		No

Make:		Model:		Year or SN:

Vent connected to?		Common shaft		Individual duct

If individual, duct exits through:		Roof		External wall

Does the local bathroom fan have backdraft dampers?		Yes		No

Is there a working vented kitchen exhaust fan/hood?		Yes		No

Make:		Model:		Year or SN:

Vent connected to?		Common shaft		Individual duct

If individual, duct exits though:		Roof		External wall

Does the kitchen exhaust have a backdraft damper?		Yes		No

Does exhaust use a central fan serving exhausts from other apt? Yes		No

Fan location:

Does the exhaust contain a backdraft damper?		Yes		No

Visible cracks and/or unsealed areas on interior walls		Yes		No

Connection wall-wall, wall-ceiling or wall-floor

Around cabinets, doors and sinks

Around pipes and electrical outlets

Behind baseboards

Visible cracks and/or unsealed areas on the exterior walls Yes No

Connection wall-wall, wall-ceiling or wall-floor

Around windows

Around pipes and electrical outlet

Behind baseboards

Which material is the door made of? Wood Metal

Does the door close tightly (without air gap)? Yes No

If no, explain:

Total number of windows:

Location	Size (ft)	Glazing	Frame	Close tightly?	Broken?	Condensation?

Location: Entry side (E), Back (B), Left (L) or Right (R) as walking in

Glazing: Single (S) or Double (D) pane

Frame: Wood (W), Vinyl (V), Aluminum (A)

Thermal comfort, heating/cooling

Is there a programmable thermostat? Yes No

Is there an apartment HVAC system? Yes No

Make: Model: Year or serial number:

Compressor make: Model: Year or SN:

Number of return registers:

Number of supply registers:

Type of ductwork: None Wall cavity Ducts

Are ducts in an unconditioned space? No, in interior wall cavities Yes in exterior wall cavities Yes in attic Yes in crawl space

Visible cracks/leaks in cavities or unsealed ducts? Yes No

Explain:

Visible thickness of duct insulation?

None none to 1 inch 1-2 inch > 2 inch

Current filter efficiency: Size (L x W x Thickness):

Type of filter: Fiberglass Electronic Pleated

Make: Model:

Location Filter slot Return grille

Bypass? Yes No Explain

Space available for thicker filter? No up to 2 inch up to 4 inch

Type of heating unit: None Elec Gas Other:

Type: Gas wall furnace Gas furnace in closet Electric baseboard Electric furnace Space heater

Location: Year or SN:

Make: Model:

Capacity: Efficiency:

Vented outside Yes No

Direct vent Yes No

Fan-forced Yes No

Pilot light Yes No

Deteriorated heat exchanger Yes No

Is the venting system obstructed Yes No

Type of cooling unit: None Central Window Other:

Location: Year or SN:

Make: Model:

Capacity: Efficiency:

Leaky/condensation? Yes No

Is the venting system obstructed? Yes No

AC cover present? Yes No

Are there any portable space heaters? Yes No

Number of ceiling fans:

Number of portable fans:

Source Control/Exhausts

Type of cooking appliance (stove/oven):	Elec	Gas		Other:
Year or SN:	Make:		Model:	
Location:	Internal wall	External wall		
With oven	Yes		No	
Pilot light	Yes		No	
Do all burners ignite when turned on?	Yes		No	
Does flame look good (shape & color)?	Yes		No	

Presence of other cooking devices?	Yes	No
Microwave		
Toaster oven		
Toaster		

Type of water heater in the apartment	None	Elec	Gas	Other:
Year or serial number:	Make:		Model:	
Fan forced	Yes		No	
Pilot light		Yes		No
Is pilot cover in place (or open)?		Yes		No
Is the venting system obstructed?		Yes		No
Is air inlet clear of dust and debris?	Yes		No	
Insulation of water tank and lines?	Yes		No	

Other combustions appliances	Yes	No	
Explain:			
Year or SN:	Make:		Model:

Pilot light	Yes	No
Vented	Yes	No

CO monitors/alarms	Yes	No
Working?	Yes	No

Signs of past/current mold issues	Yes	No

Where (sketch)

Size (ft^2)

Possible cause

Water/moisture visible damage (windows, sinks, toilet, AC)	Yes	No

Location:

Likely source:

Potential pollutant sources	Yes	No

Cleaning products

Incenses

Candles

Air Fresheners

Pressed wood furniture (area- ft^2):

Cabinetry without laminate cover (area- ft^2):

Other:

Air cleaning devices	Yes	No

Make: Model:

Humidifier	Yes	No

Make: Model:

Appliances

Refrigerator

Year or SN: Make: Model:

Dishwasher present? Yes No

Year or SN: Make: Model:

Clothes washer present? Yes No

Year or SN: Make: Model:

Clothes dryer present? Yes No

Year or SN: Make: Model:

Type: Gas Elec

Vents to: Indoors Outdoors via wall Outdoors via roof
Outdoors via common shaft

Number of light fixtures:

Presence of any potentially unsafe electrical connections? Yes No

Explain:

Photographs taken? Yes No

Notes:

Sketch:

A2.7 Protocols for Measurements to be Implemented During Apartment Inspections and Data Collection Forms

Apartment ID Code: ____

Inspector Name(s): ____

Date: ______________________________ Time: ______________________________

Insulation

To acquire information regarding the current wall and ceiling insulation we made small holes and observed the type of insulation present with a boroscope[2]. We checked for current insulation in exterior walls and above ceiling separately. First, we drilled a few small holes away from all electrical wiring and used a boroscope with integrated light source to observe inside the wall cavity and determine whether insulation was present, and what type is present.

Insulation level:

External wall	No	Yes	Type/level:
Ceiling	No	Yes	Type/level:

Leakage area and smoke test

A pressurization test was performed in each apartment to measure the effective leakage area and to identify the locations of major leaks. This test enabled a comparison of the pre- and post-retrofit leakage area and an evaluation of the effectiveness of the air sealing retrofit. The leakage area measurement did not discriminate between inter-

[2] This protocol for checking for presence of insulation in walls was subsequently determined to be unreliable. Larger holes and direct visual examination (without a boroscope) is recommended.

apartment leakage and leakage to outdoors, thus, the resulting leakage area is not a good predictor of air exchange with outdoors. Consequently, the measurements of leakage area were not inputs to the retrofit selection protocol. Inter-apartment leakage was always sealed when permitted by the owner and tenant, unless there was a risk of combustion pollutant back drafting that would be aggravated by envelope sealing. We also paired the leakage area test with a smoke flow test to identify the types and locations of major leaks, which are valuable information for the subsequent air leakage retrofit.

We performed the air leakage according to ASTM E779 by measuring the airflow through the blower door fan at various pressure differences between inside and outside. With these data, we ran a linear regression to estimate critical parameters (coefficients C and n) and subsequently the leakage area at a standard pressure (i.e., 4 Pa) and the airflow at 50 Pa (CFM_{50}).

Additionally, we used diagnostic smoke to identify the location of the major leaks. We expected leaks at typical locations including around plumbing, doors, windows and cabinets, behind baseboards and at the connection between walls and floors/ceiling. The test consists of generating smoke with chemical smoke puffer near suspected leaks, with the apartment pressurized, and visually observing where smoke is expelled through the suspected leak.

Test	Pressure difference (Pa)	Fan flow (CFM)
Pressurization		
1		
2		
3		
4		
5		

Reference outside pressure (Pa):

Location of major air leakages (diagnostic smoke):

Noise

We performed noise assessments to characterize the potential discomfort caused by the following devices, if present:

- Central HVAC system (fan-only, heating and cooling mode)
- AC window unit
- Wall furnace
- Bathroom fan
- Kitchen hood exhaust

We performed the measurements and assessment using a modified version of the Home Ventilating Institute Publication 915 – HVI Loudness Testing and Rating Procedure. This publication is designed for loudness testing in the laboratory and not in the field. As a consequence, to be able to apply the test to equipment in the field, the following modifications were incorporated into the protocol:

- We did not use the "reference sound source (RSS)" sound measurement, only the "fan" and "background (bgd)". First, when possible, we turned off any other known noise generating devices including TVs, radios and computers. Then we performed a pressure measurement with the "fan+bgd" and then with just the "bgd".
- The measurement device was warmed up for 5 minutes instead of 30 minutes
- All the windows were closed, while all the interior doors will be completely open.

We used the following setups to conduct the sound pressure test:

- Central HVAC system in closet: the door of the closet was completely closed and the measurement was conducted right in front of the closet at a distance and height off the floor of 5 feet each.
- AC window and wall furnace: the measurement was conducted right in front of the device at a distance and height off the floor of 5 feet each.
- Bathroom exhaust fan: with bathroom doors open and windows closed, we performed the measurement in the center of the bathroom at a height off the floor of 5 feet
- Kitchen hood exhaust: the microphone was located right in front of the kitchen stove at a distance of 1 foot and height off the floor of 5 feet.

If a device operated at different speeds (or settings), measurements were repeated at each setting.

Data collection table (db)

Test	HVAC system	Heating system	Air-Conditioner	Bathroom exhaust	Kitchen exhaust
Background					
Fan + bgd					

Exhaust flow rates

The flow rates through local exhaust vents (kitchen and bathroom) were characterized using a Duct Blaster®. The methodology consisted of connecting the Duct Blaster® to the flex duct in "pressurization" configuration, while the other end of the flex duct was connected to a capture hood, typically a cardboard box with a perforated irrigation tube to serve as a tap for the average pressure inside the box, with the box placed over the exhaust. While the exhaust fan was operated, we measured the pressure difference between the cardboard box and the room. Finally, we adjusted the Duct Blaster® flow rate to zero the pressure difference and recorded the Duct Blaster® flow. For information on measuring air flow rates in homes see Walker et al. (2003).

Kitchen hood flow rate: cfm/setting cfm/setting cfm/setting

Bathroom fan flow rate: cfm

Whole unit exhaust: cfm

Combustion appliances

Furnace

Combustion Appliance Zone (CAZ) worst-case depressurization test (Building Performance Institute 2012) Pa

Backdrafting/spillage

	First 60 sec of operation	*After 60 sec of operations*
Worst case		
Natural conditions		

Water heater:

Combustion Appliance Zone (CAZ) worst-case depressurization test: *Pa*

Backdrafting/spillage

	First 60 sec of operation	*After 60 sec of operations*
Worst case		
Natural conditions		

A2.8 Models Used to Estimate the IAQ Impacts of Retrofits

In order to estimate the IAQ impacts of retrofits, when feasible we estimated the pre- and post-retrofit pollutant concentrations using the EPA IAQX model (http://www.epa.gov/ordntrnt/ORD/NRMRL/appcd/mmd/iaqx.html) that utilizes simple mass-balance models using information and data collected from the inspections and measurement as well as literature values as inputs. This section provides the instructions for estimating the IAQ impacts of retrofits.

Specifically, we used the IAQX software to estimate the IAQ benefit for the following retrofit actions:

- Remove appliances with pilot light
- Install bathroom exhaust
- Install kitchen range hood
- Remove high pollutant emitting gas stove

Table A2.2: Parameters and assumptions used to estimate impacts of retrofits*

Retrofit	Contaminant	Indoor emission rate	Fraction time emitting	Outdoor conc.	Decay
Remove appliances with pilot light	NO_2	11 mg/h [D]	Always	0.026 mg/m^3 [A]	Air exchange rate (0.3 h^{-1}) and deposition (1 h^{-1})
Install intermittent bath exhaust	Moisture (RH)	2,600 g/h shower [E]	30 min/d	62% [B]	Air exchange rate (0.3 h^{-1}) Bath exhaust flow rate= 25 L/s × 0.5/24 (fraction on)
Install kitchen hood	NO_2	97 mg/h [D]	1 h/day [F]	0.026 mg/m^3 [A]	Air exchange rate (0.3 h^{-1}) Kitchen hood flow rate= 50L/s × 1/24 (fraction on)
	PM2.5	4 mg/h [C]		11 $\mu g/cm^3$ [A]	
Replace high pollutant emitting stove	NO_2	97 mg/h [D]	1 h/day [F]	0.026 mg/m^3 [A]	Air exchange rate (0.3 h^{-1})
	CO	1,404 mg/h [G]		0.4 ppm [A]	

[A] California Air Resource Board (CARB) – Alameda County [B] National climatic data center, NOA – San Francisco

[C] Girman et al., 1982 [D] Moschandreas et al., 1986 [E] TenWolde and Pilon, 2007 [F] Coward and Raw, 1996

[G] Dimitroulopoulou et al., 2006 *in addition to these inputs, the apartment volume was a model input

In addition to the EPA IAQX model, a few other simple models or data from published studies were utilized to estimate the impact of some retrofits. These include the following retrofit actions:

- Upgrade HVAC filtration (this is a a-priori action)
- Add heating recovery ventilation
- Add air-movement device (in presence and absence of AC)
- Upgrade window
- Add wall insulation
- Add films/shading to existing windows
- Replacement of a noisy device

Upgrade HVAC filtration

A simple mass balance model was utilized to estimate the predicted reduction in indoor concentrations or particles less than 2.5 micrometers (PM2.5) achievable with improved filtration. For typical conditions, the model predicts that a MERV 11 filter should be able to reduce the indoor PM2.5 concentration by approximately a fourth relative to the estimated concentration resulting with a low efficiency filter (MERV<5).

Heat recovery ventilators (HRV) and energy recovery ventilators (ERV)

Mechanical ventilation of a residence can impose an energy penalty due to the increased need to condition of the incoming air. HRV and ERV systems are capable of recovering some of energy present in the outgoing air therefore potentially reducing the energy penalty compared to exhaust-only systems; however, HRV systems employ a second fan and generally increase fan energy relative to an exhaust-only fan. Wray et al. (2000) and Walker and Sherman (2008) investigated the energy consequences of different ventilation strategies. Based on their reported findings we estimated an annual energy penalty of approximately \$4-5/100 ft^2 compared to natural infiltration for the climates of interest in the current study. However, HRVs and ERVs are balanced ventilation systems that supply and exhaust roughly the same amount of air and that, consequently, reduce the risks of inter-apartment pollutant transport back drafting of combustion appliances because they do not depressurize apartment.

Air-moving device

Air moving devices are widely employed to maintain occupants cool in warm climates. They impact comfort, since they provide a cooling effect, and can save energy due to the reduced use of the air conditioning system, if this is present. The evaluation of the potential benefits depended on the initial condition of the apartment including the presence of an air-conditioning system, the orientation of the main exterior wall and windows as well as the story where the apartment is located.

For apartment without air conditioning (AC), the fans will have a negative energy impact due to fan energy penalty; however, they will provide a cooling effect and therefore a thermal comfort improvement. This improved comfort was estimated using the SET index assuming an indoor temperature of 25 ^{o}C, air velocity due to presence of the fan of 1 m/s and a clothing level (clo) of 0.5.

In apartments with AC, the fans should have an energy benefit due to reduced use of the AC. A standing fan is reported to have a cooling effect of approximately 2 ^{o}C (Schiavon and Melikov, 2009) and we estimated the energy savings due to the reduced cooling load by increasing the cooling temperature setting in the HES webpage by 2 ^{o}C.

Upgrade Windows

Higher quality windows, besides having energy benefits due to the reduced heat exchanged with outdoors, also influence occupant comfort due to the reduction in drafts, and reduced thermal radiation heat exchanged between the body and the window, and reduced solar radiation transmitted by the window during the summer. The comfort benefits will depend on the location climate. For this evaluation, for the location of interest, we considered only the winter comfort impact. Huizenga et al. (2006) report (their Table 16) the minimum outdoor temperature for which a window could still provide sufficient comfort. We compared this value to weather data for a location to predict how often a specific window will result in uncomfortable conditions. We assigned a +1 comfort score increment for every 5% of frequency of occurrence.

Wall Insulation

Wall insulation is also expected to have a comfort benefit due to reduced thermal radiation heat lost from the body to an insulated wall during cold weather. Also, comfort may improve due to what is known as "takeback" effect, which refers to the fact that occupant may increase the indoor temperature in the winter due to reduced energy costs. Based on (Fuller et al., 2009), we assigned a +1 comfort score for wall insulation.

Noisy device

We assigned a +1 comfort score when replacing a device producing a noise level of 55 dB(A) with a quiet unit. Furthermore, we assigned additional +1 comfort scores for every 10 dB(A) increment (i.e., 65 dB(A) = +2; 75 dB(A) = +3).

A2.9 Instructions for using Home Energy Saver (HES) During Application of the Retrofit Selection Protocol

The Home Energy Saver – HES – webpage (http://hes.lbl.gov) was used to obtain a list of retrofit recommendations and estimates of potential savings that could be achieved. After detailed information regarding the residence is input, the retrofits to upgrade the energy efficiency of the dwelling are suggested and the associated estimates of costs, savings and payback times are provided. Although HES focuses on single-family homes, it has a town house option that was used in the current study and future versions of HES will have expanded capabilities for apartments.

During the retrofit selection protocol we made the following choices to apply the analysis to an apartment:

- Shape = Town house
- For apartments not on the building ground floor:
    - Foundation type = Slab-on-grade
    - Foundation insulation level = max (R-19)
    - Insulation level of floor above basement/crawlspace type = max (R-38)
- For apartments not on the building top floor
    - Insulation level of the attic floor = max (R-60)

For the analyses, we utilized the estimated yearly savings and the estimated added cost. For what the HES program defines as "the first type of upgrade", which is selecting a more efficient product when replacing an existing one, we apply the (additional) estimated cost provided by HES to the estimated cost of a standard-efficiency new product.

A2.10 Assumed Retrofit Costs Used when HES does not Estimate Costs

In order to select retrofits capable of maximizing the benefits compared to the investment undertaken, we needed to quantify an expected cost of each retrofit action. For the retrofits not considered by the HES webpage, we estimated the approximate costs based on the materials and labor required by conducting a web search. The material costs were added to the predicted labor costs, based on the estimated labor hours needed and typical labor cost rate. Table 1 presents preliminary predicted costs for a range of retrofit actions that consider both the material cost and the labor cost of the action. The labor cost is equal to the required time for the task multiplied by the labor rate, which will vary with the location.

The actual installed costs for retrofits will vary depending on the specific equipment and materials used as well as the design and configuration of the apartment and building considered. However, we used these estimates to predict the cost of each retrofit and, therefore, to be able to select the desired retrofit actions.

Table A2.3: Estimated approximate cost for the retrofits not addressed by HES (organized from low to high cost)

Retrofit	Material cost ($)	Labor Time (h)	Total cost ($)* at $60/h for labor
Improve HVAC filtration	10-30	0.5	40-60
Install cover on window air conditioners	30-50	0.5	60-80
Install CO monitor	30-100	0.5	60-130
Add film/shading to window (per window)	50-300	0.5	80-530
Add portable air-moving devices	100-200	-	100-200
Add dehumidifier	100-400	-	100-400
Repair window AC	0-100	1	160-360
Repair water heater	0-100	1	160-360
Repair stove	0-100	1	160-360
Repair heating device	0-200	1	160-460
Water seal in bath	100-200	2	220-320
Replace vented bath fan	200-300	0.5	230-330
Fix leaking water pipes causing water damage	100-500	3	280-680
Air sealing between shaft and apartments	300-500	2	420-620
Replace stove	400-1,000	1	460-1,060
Replace window AC	400-1,500	1.5	490-1,690
Install vented bath fan with exhaust through external wall	400-600	2	520-720
Install HRV	500-700	2	620-820
Replace heating device	500-2,000	3	680-2,180
Replace water heater	600-1,500	2	720-1,620
Replace vented kitchen range hood	700-1,000	2	820-1,120
Install vented kitchen range hood on external wall	700-1,000	2	820-1,120
Install vented kitchen range hood on internal wall	700-1,000	3	880-1,180

***A labor rate of $60/h was assumed for these preliminary estimates.**

A2.11: Procedure for Assigning Impact Scores and Ranking Retrofits

In order to maximize the benefit of the retrofit package implemented, the retrofits considered first received a score for each benefit category that was likely to be impacted out of the three possible categories (energy, IAQ, comfort). Table 1 (main text of this document) indicates the impacted benefit categories and Table A2.4 indicates the type of analysis conducted for each candidate retrofit. Depending on the retrofit considered, the analysis was based on data from inspections, measurements, calculations or a combination of these sources. Additionally, the calculations were performed on the IAQX software or HES webpage. The "Group 1" label under the "Analysis" column identifies the retrofits that were selected a-priori without analysis. Letters in the "Analysis" column identify the methods used to determine the retrofit score.

Table A2.4: Lists of the candidate retrofits with the types of analysis used for evaluate their benefits and assigning the scores.

Retrofit		Analysis
Ventilation		
Seal interior connections between apartment and rest of building		Group 1*
Seal external wall connections[1]		Group 1
Install balanced heat recovery ventilation (HRV)[2]		Group 1-C
Install continuous vented bath fan for source control & mechanical ventilation[2]		Group 1-C/IAQX
Replace continuous vented bath fan for source control & mechanical ventilation because[2]	Noisy	Group 1-M
	Low flow	Group 1-M
Install intermittent (e.g. timer controlled, humidity sensing, occupant sensing) vented bath fan for source control only[2]		Group 1-C/IAQX
Replace intermittent (e.g. timer controlled, humidity sensing, occupant sensing) vented bath fan for source control only because[2]	Noisy	Group 1- M
	Low flow	Group 1-C/IAQX
Install vented kitchen range hood exhaust system[2]		Group 1-C
Replace existing vented kitchen hood because[2]	Inefficient	Group 1-C/IAQX
	Noisy	Group 1-M
Install cover on window air conditioners		I+J
Thermal comfort/Heating & cooling		
Add external wall insulation		I+C/HES
Add ceiling insulation in top-floor apartments		I+C/HES
Install programmable thermostat		I+C/HES
Replace air conditioner because	Inefficient	I+C/HES
	Noisy	M
	Water leak	I+J
Repair air conditioner because	Inefficient	I+J
	Noisy	M
	Water leak	I+J
Replace heating device because	Inefficient	C/HES
	Noisy	M
	Polluting	M
Repair heating device because	Inefficient	I+J
	Noisy	M
	Polluting	M
Replace unvented heating device with a vented one (ensure adequate venting for all combustion appliances)		I+J
Seal and insulate HVAC ducts in unconditioned space and cavities		I+C/HES
Improve HVAC filtration		Group 1-C
Add air-moving device (fan)	With AC	J+C
	Without AC	I+J
Replace broken windows		I+J
Upgrade existing windows		C/HES

Table A2.4 Continued

Source Control &	
Fix leaking water pipes causing water damage	I+J
Water seal in bath	I+J
Limited scale moisture and mold retrofits (budget limited to < $2K)	I+J
Replace pilot ignition combustion appliances (gas stove, furnace, water heater) with comparable or more efficient units with electronic ignition	I+C/IAQX
Replace combustion appliance (furnace, water heater) with potential backdrafting issues with forced combustion appliance	M+J
Replace combustion appliance (furnace, water heater) with faulty vent	I+J
Vent outside existing dryer	I+J
Install CO monitor	I+J
Appliances	
Energy efficient lighting upgrade (i.e., CFLs)	I/HES
Replace inefficient water heater with a more efficient one	C/HES
Replace inefficient refrigerator	I/HES
Upgrade water heating system (i.e., install low flow showerhead, add insulation)	Group 1

[1] Sealing external walls is an a--priori measure if mechanical ventilation was also provided

[2] Alternative a-priori actions to meet whole-unit and local exhaust ventilation requirements

*Group 1 indicates an a-priori retrofit, thus, a retrofit for which benefits analysis was not required.

I = inspection, M = measurement, C = calculation, J= judgment, HES= HES was used to perform energy calculations, IAQX= IAQX was used to perform IAQ calculations.

Following the analyses, the scores were assigned based on the predicted impact and, when possible, on the estimated change in a critical metric (i.e., yearly savings, pollutant concentration). This change was compared to a standard or to a typical value reported in the literature for the metric. For NO_2 and PM2.5, each score level equals to 10% of the California Air Resource Board (ARB) annual standard. Additionally, we assigned an extra IAQ score of +1 to the retrofits that we predict would remove a significant ultrafine particle source (e.g., combustions).

Table A2.5 provides the boundaries for changes in IAQ and comfort parameters used for assigning the scores based on the predicted impacts, when feasible. Subsequently, for each retrofit, the total impact score was obtained by adding the single scores in each impact category. For retrofits impacting more than one parameter in the same category (i.e., more than one pollutant in the IAQ category) the total IAQ category score was the sum of the single parameter scores up to maximum of +3. Subsequently, the scores for each category (IAQ, energy and comfort) was summed to obtain a final score on a -9/+9 scale.

Table A2.6 shows the indoor air quality and comfort points determined for the current project. These point assignments in the indoor air quality and comfort categories can be used as defaults for similar apartments in California. No default points are provided in the energy category since the HES Program is readily available for estimation of energy savings.

Table A2.5 Criteria for assigning scores in each category based on predicted impacts.

Category	Parameter	Impact Score					
		-3	-2	-1	+1	+2	+3
IAQ: predicted conc. change (μg/m^3)	NO_2[A]	<(11.2)	(5.6-11.2)	(0-5.6)	0-5.6	5.6-11.2	>11.2
	PM2.5[B]	<(2.4)	(1.2-2.4)	(0-1.2)	0-1.2	1.2-2.4	>2.4
	Moisture (RH)	<(10)	(5-10)	(0-5)	0-5	5-10	>10
Energy: predicted ($)	Yearly savings	<(100)	(50-100)	(0-50)	0-50	50-100	>100
Comfort: predicted change	PPD[C]	<(10)	(5-10)	(0-5)	0-5	5-10	>10

[A] ARB annual = 56 μg/m^3 [B] ARB annual = 12 μg/m^3 [C] PPD is predicted percent dissatisfied with thermal comfort from the ASHRAE thermal comfort standard (ASHRAE 2010)

Table A2.6: Table 3. Retrofit benefit scores and form for compiling cost normalized scores.

Retrofit		Score				Cost ($)[B]	Score/$
		IAQ	Energy [A]	Comfort	Total		
Install cover on window air conditioners			+1		1		
Add external wall insulation			HES	+1	HES+1		
Add ceiling insulation in top-floor apartments			HES	+1	HES+1		
Install programmable thermostat			HES		HES		
Replace air conditioner because	Inefficient		HES		HES		
	Noisy			+1	1		
	Water leak	+3			3		
Repair air conditioner because	Inefficient		HES		HES		
	Noisy			+1	1		
	Water leak	+3			3		
Replace heating device because	Inefficient		HES		HES		
	Noisy			+1	1		
	Polluting	+3			3		
Repair heating device because	Inefficient		HES		HES		
	Noisy			+1	1		
	Polluting	+3			3		
Replace unvented heating device with a vented one (ensure adequate venting for all combustion appliances)		+1	HES		HES+1		
Seal and insulate HVAC ducts in unconditioned space and cavities			HES		HES		
Add air-moving device (fan)	With AC		+1		1		
	Without AC			+1/2/3[C]	+1/2/3		
Replace broken windows			+2/3[D]	+1	3/4		
Upgrade existing windows			HES	+1	HES+1		
Fix leaking water pipes causing water damage		+3			3		
Water seal in bath		+1			1		
Limited scale moisture and mold retrofits (budget < $2K)		+3			3		

Table A2.6 Continued

Replace pilot ignition combustion appliances (gas stove, furnace) with comparable or more efficient units with electronic ignition	+1	HES		HES+1		
Replace combustion appliance (furnace, water heater) with potential back drafting with a forced combustion appliance	+1	HES		HES+1		
Replace combustion appliance (furnace, water heater) with faulty vent	+1	HES		HES+1		
Replace inefficient water heater with a more efficient one		HES		HES		
Install CO monitor	+1			1		
Energy efficient lighting upgrade (i.e., CFLs)		HES		HES		
Vent outside existing dryer	+2/3[E]			2/3		
Replace inefficient refrigerator		HES		HES		

[A] The label HES indicates that the energy score was based on the HES yearly savings using the criteria outlined on Table A2.5.

[B] Obtained from Table A2.3

[C] A +1 score increment was assigned for each of the following conditions: cooling degree days >560 ^{o}C-day; apartment on top floor; apartment with south exposure.

[D] We assigned a +2 or +3 based on window conditions and apartment location.

[E] We assigned a +2 for an electric dryer and a +3 for a gas dryer.

A2.12 Appendix A2 References

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APPENDIX A3: Energy Use Data

Table A3.1: Annual energy use in B1

Energy type	gas	gas	gas	gas	gas	gas	elec	elec	elec	elec	elec	elec
Season	yr	yr	yr	yr	yr	yr	yr	yr	yr	yr	yr	yr
Period		Pre	Post	Pre	Post	Post-Pre		Pre	Post	Pre	Post	Post-Pre
Parameter	days	HDD/d (°C)	HDD/d (°C)	kWh/d	kWh/d	change	days	CDD/d (°C)	CDD/d (°C)	kwh/d	kwh/d	change
B1A1	363	3.99	3.87	31.9	26.1	-18%	365	1.63	2.07	18.6	17.1	-8%
B1A4	363	3.99	3.87	40.7	26.7	-35%	365	1.63	2.07	14.1	11	-22%
B1A5	363	3.99	3.87	32.2	27.5	-15%	155	1.14	1.27			
B1 total				35.0	26.8	-23%				16.4	14.1	-14%
B1 "n-1" total						-16%						
B1A2c	363	3.99	3.87	29.9	38.4	28%	365	1.63	2.07	11.6	14.2	22%
B1A4c	331	4.36	4.17	37.5	36.0	-4%	365	1.63	2.07	6.9	9.6	40%
B1A5c												
B1A6c												
B1A8c	363	3.99	3.87	36.9	32.8	-11%	365	1.63	2.03	12.9	14.5	12%
B1A9c	304	4.78	4.62	27.0	25.2	-7%	336	1.41	1.73	13.3	13.9	5%
B1A10c												
B1A11c	363	3.99	3.87	33.7	34.6	3%	365	1.63	2.07	13.2	16.3	23%
B1A13c							362	1.60	2.07	6.5	13.1	102%
B1c total				33.1	33.6	2%				10.7	13.6	27%
B1c "n-1" total						-5%						21%

Table A3.2: Annual energy use in B2.

Energy type	gas	gas	gas	gas	gas	gas	elec	elec	elec	elec	elec	elec
Season	yr	yr	yr	yr	yr	yr	yr	yr	yr	yr	yr	yr
Period		Pre	Post	Pre	Post	Post-Pre		Pre	Post	Pre	Post	Post-Pre
Parameter	days	HDD/d (°C)	HDD/d (°C)	kWh/d	kWh/d	change	days	CDD/d (°C)	CDD/d (°C)	kwh/d	kwh/d	change
B2A2	362	4.53	4.44	19.9	13.2	-34%	362	0.23	0.09	7.1	6.5	-9%
B2A4	362	4.53	4.44	27.2	27.8	2%	362	0.23	0.09	6.8	6.5	-5%
B2A5	362	4.53	4.44	31.4	28.1	-10%	362	0.23	0.09	6.8	6.9	2%
B2A6	362	4.53	4.44	79.4	85.8	8%	362	0.23	0.09	17.4	17.8	2%
B2 total				39.5	38.7	-2%				9.5	9.4	-1%
B2 "n-1" total						0%						0%
B2A2c	362	4.53	4.44	27.8	30.2	8%	362	0.23	0.09	9.2	9.7	6%
B2A3c	362	4.53	4.44	8.2	11.1	36%	362	0.23	0.09	4.7	5.7	22%
B2A4c	362	4.53	4.44	10.3	11.7	14%	362	0.23	0.09	8.8	7.4	-15%
B2A5c	362	4.53	4.44	16.7	13.8	-18%	362	0.23	0.09	5.4	5.3	-3%
B2A6c	362	4.53	4.44	35.7	39.6	11%	362	0.23	0.09	5.9	5.4	-8%
B2A7c	331	4.13	3.98	12.9	13.5	5%	331	0.26	0.1	6.9	5.8	-15%
B2A9c	362	4.53	4.44	44.5	44.0	-1%	362	0.23	0.09	10.2	9.3	-9%
B2c total				22.4	23.5	5%				7.3	7.0	-5%
B2c "n-1" total						3%						-8%

Table A3.3: Annual energy use in B3.

Energy type	gas	gas	gas	gas	gas	gas	elec	elec	elec	elec	elec	elec
Season	**year**	**year**	**year**	**year**	**year**	**year**	**year**	**year**	**year**	**year**	**year**	**year**
Period		**Pre**	**Post**	**Pre**	**Post**	**Post-Pre**		**Pre**	**Post**	**Pre**	**Post**	**Post-Pre**
Parameter	**days**	**HDD/d (°C)**	**HDD/d (°C)**	**kWh/d**	**kWh/d**	**change**	**days**	**CDD/d (°C)**	**CDD/d (°C)**	**kwh/d**	**kwh/d**	**change**
B3A1*	304	3.51	3.13	24.6	26.4	7%	364	3.20	4.07	6.6	9.0	36%
B3A2	363	3.47	2.79	24.3	15.8	-35%	363	3.20	4.07	7.8	6.4	-18%
B3A4	332	3.36	2.87	31.1	27.8	-10%	332	3.48	4.38	17	20.1	18%
B3A5	333	3.36	2.87	50.4	45.1	-10%	333	3.48	4.38	13.5	19.9	47%
B3A6	363	3.47	2.79	44.0	33.1	-25%	363	3.20	4.07	18.5	22.2	20%
B3 total				35.0	29.5	-16%				12.6	15.3	22%
B3 “n-1” total						-10%						14%
B3A1c	363	3.47	2.79	28.7	30.8	7%	363	3.20	4.07	26.2	22.4	-15%
B3A2c	363	3.47	2.79	34.3	28.4	-17%	363	3.20	4.07	13.6	13.9	2%
B3A3c	363	3.47	2.79	23.4	28.4	21%	363	3.20	4.07	11.2	15.9	42%
B3A4c	335	3.33	2.87	24.9	24.0	-4%	335	3.42	4.38	18.8	23.2	23%
B3A8c	363	3.47	2.79	25.5	19.3	-24%	363	3.20	4.07	15.8	17.9	13%
B3A9c	363	3.47	2.79	20.5	12.3	-40%	363	3.20	4.07	24.5	22.8	-7%
B3c total				26.2	23.9	-9%				18.3	19.3	5%
B3c “n-1” total						-3%						3%

Table A3.4: Winter gas and summer electricity use in B1.

Energy type	gas	gas	gas	gas	gas	gas	elec	elec	elec	elec	elec	elec
Season	win	win	win	win	win	win	sum	sum	sum	sum	sum	sum
Period		Pre	Post	Pre	Post	Post-Pre		Pre	Post	Pre	Post	Post-Pre
Parameter	days	HDD/d (^oC)	HDD/d (^oC)	kWh/d	kWh/d	change	days	CDD/d (^oC)	CDD/d (^oC)	kwh/d	kwh/d	change
B1A1	120	8.84	8.63	43.7	39.8	-9%	120	4.50	5.22	27.9	17.1	-39%
B1A4	120	8.84	8.63	68.0	32.8	-52%	120	4.50	5.22	23.6	19.7	-17%
B1A5	120	8.84	8.63	43.7	41.3	-5%	120	4.50				
B1 total				51.8	38.0	-27%				25.8	18.4	-29%
B1 “n-1” total						-7%						
B1A2c	120	8.84	8.63	46.9	60.7	29%	120	4.50	5.22	15.2	21.3	40%
B1A4c	120	8.84	8.63	61.8	56.0	-9%	120	4.50	5.22	8.1	13.5	67%
B1A5c												
B1A6c												
B1A8c	120	8.84	8.63	41.6	36.0	-13%	120	4.50	5.08	13.8	17.6	28%
B1A9c	120	8.84	8.63	36.0	31.4	-13%	91	4.62	4.96	17.0	18.3	8%
B1A10c												
B1A11c	120	8.84	8.63	46.6	51.3	10%	120	4.50	5.08	20.3	25.5	26%
B1A13c	120	8.84	8.63	37.8	40.4	7%	115	4.50	5.30	13.4	20.6	54%
B1c total				45.1	46.0	2%				14.5	19.5	34%
B1c “n-1” total						-4%						31%

Table A3.5: Winter gas and summer electricity use in B2.

Energy type	gas	gas	gas	gas	gas	gas	elec	elec	elec	elec	elec	elec
Season	win	win	win	win	win	win	sum	sum	sum	sum	sum	sum
Period		Pre	Post	Pre	Post	Post-Pre		Pre	Post	Pre	Post	Post-Pre
Parameter	days	HDD/d (^{o}C)	HDD/d (^{o}C)	kWh/d	kWh/d	change	days	CDD/d (^{o}C)	CDD/d (^{o}C)	kwh/d	kwh/d	change
B2A2	87	5.33	7.51	31.9	19.0	-40%	90	0.31	0.06	7.0	6.2	-11%
B2A4	88	5.33	7.51	39.8	44.5	12%	90	0.31	0.06	6.9	5.9	-14%
B2A5	88	5.33	7.51	56.5	40.1	-29%	90	0.31	0.06	6.8	6.4	-6%
B2A6	88	5.33	7.51	105.2	120.4	14%	90	0.31	0.06	18.4	18.9	3%
B2 total				58.5	56.1	-4%				9.8	9.4	-4%
B2 “n-1” total						-1%						-5%
B2A2c	88	5.33	7.51	27.8	61.8	122%	90	0.31	0.06	8.8	10.3	17%
B2A3c	88	5.33	7.51	16.4	21.7	32%	90	0.31	0.06	4.3	4.9	14%
B2A4c	88	5.33	7.51	14.7	21.1	44%	90	0.31	0.06	8.9	6.9	-23%
B2A5c	88	5.33	7.51	27.8	18.8	-33%	90	0.31	0.06	5.6	5.8	3%
B2A6c	88	5.33	7.51	48.6	57.7	19%	90	0.31	0.06	5.5	5.2	-4%
B2A7c							90	0.31	0.06	6.1	6.8	11%
B2A9c	88	5.33	7.51	68.3	66.5	-3%	90	0.31	0.06	9.6	8.1	-15%
B2c total				33.9	41.3	22%				7.0	6.9	-2%
B2c “n-1” total						12%						4%

Table A3.6: Winter gas and summer electricity use in B3.

Energy type	gas	gas	gas	gas	gas	gas	elec	elec	elec	elec	elec	elec
Season	win	win	win	win	win	win	sum	sum	sum	sum	sum	sum
Period		Pre	Post	Pre	Post	Post-Pre		Pre	Post	Pre	Post	Post-Pre
Parameter	days	HDD/d (°C)	HDD/d (°C)	kWh/d	kWh/d	change	days	CDD/d (°C)	CDD/d (°C)	kwh/d	kwh/d	change
B3A1*	121	8.61	7.09	32.5	42.2	30%	121	8.60	9.83	11.8	16.9	43%
B3A2	121	8.17	7.09	34.6	21.1	-39%	121	8.63	9.82	11.1	7.6	-32%
B3A3	91	6.15	4.29	34.6	31.4	-9%	121	8.63	9.82	28.6	44	54%
B3A4	121	8.17	7.09	45.7	44.2	-3%	121	8.63	9.82	28.5	32.3	13%
B3A5	121	8.17	7.09	50.4	45.1	-10%	121	8.63	9.82	18.8	23.8	27%
B3A6	121	8.17	7.09	78.8	51.6	-35%	121	8.63	9.82	35.4	41.2	16%
B3 total				46.6	39.6	-15%				22.4	27.6	24%
B3 "n-1" total						-6%						16%
B3A1c	121	8.17	7.09	46.9	56.3	20%	121	8.6	9.83	27.6	33.4	21%
B3A2c	121	8.17	7.09	38.4	40.1	5%	121	8.63	9.82	19.3	19.8	3%
B3A3c	121	8.17	7.09	35.2	35.2	0%	121	8.63	9.82	16.4	25.4	55%
B3A4c	121	8.17	7.09	43.7	40.4	-7%	121	8.63	9.82	30.7	37.6	22%
B3A8c	121	8.17	7.09	33.4	19.0	-43%	121	8.63	9.82	27.0	28.2	4%
B3A9c	121	8.17	7.09	31.9	14.9	-53%	121	8.63	9.82	47.3	42	-11%
B3c total				38.2	34.3	-10%				28.1	31.1	11%
B3c "n-1" total						-5%						8%

*Omitted data from April both pre and post-retrofit; reported pre-retrofit gas use in April was extremely high (161 kWh/d), is suspect data.

Table A3.7: Summer gas and winter electricity use in B1.

Energy type	gas	gas	gas	gas	gas	gas	elec	elec	elec	elec	elec	elec
Season	**sumr**	**sumr**	**sum**	**sum**	**sum**	**sum**	**win**	**win**	**win**	**win**	**win**	**winter**
Period		**Pre**	**Post**	**Pre**	**Post**	**post-Pre**		**Pre**	**Post**	**pre**	**pre**	**post-Pre**
Parameter	**days**	**HDD/d (°C)**	**HDD/d (°C)**	**kWh/d**	**kWh/d**	**change**	**days**	**CDD/d (°C)**	**CDD/d (°C)**	**kwh/d**	**kwh/d**	**change**
B1A1	90	0.02	0.04	24.4	15.0	-39%	123	0.01	0.00	14.3	12.7	-11%
B1A4	90	0.02	0.04	20.5	24.7	21%	123	0.01	0.00	9.1	4.4	-52%
B1A5	90	0.02	0.04	25.1	21.5	-14%	94	0.01	0.00	17.4	16.0	-8%
B1 total				23.3	20.4	-13%				13.3	10.6	-20%
B1 "n-1" total						3%						-10%
B1A2c	90	0.04	0.04	17.4	16.9	-3%	123	0.01	0.00	10.6	9.2	-13%
B1A4c	89	0.02	0.04	15.1	18.5	22%	123	0.01	0.00	7.3	8	10%
B1A5c							123	0.01	0.00	8.8	8.2	-7%
B1A6c							117	0.01	0.00	9.6	5.7	-41%
B1A8c	90	0.02	0.04	30.3	27.0	-11%	123	0.01	0.00	14.6	12.8	-12%
B1A9c							123	0.01	0.00	12.1	12.1	0%
B1A10c							95	0.01	0.00	10.5	11.5	10%
B1A11c	90	0.02	0.04	24.1	23.1	-4%	123	0.01	0.00	10	11.7	17%
B1A13c							123	0.01	0.00	3.8	9.3	145%
B1c total				21.7	21.4	-2%				9.7	9.8	1%
B1c "n-1" total						-6%						-5%

Table A3.8: Summer gas and winter electricity use in B2.

Energy type	gas	gas	gas	gas	gas	gas	elec	elec	elec	elec	elec	elec
Season	sum	sum	sum	sum	sum	sum	win	win	win	win	win	winter
Period		Pre	Post	Pre	Post	post-Pre		Pre	Post	pre	pre	post-Pre
Parameter	days	HDD/d (°C)	HDD/d (°C)	kWh/d	kWh/d	change	days	CDD/d (°C)	CDD/d (°C)	kwh/d	kwh/d	change
B2A2	90	2.03	1.75	10.0	8.5	-15%	88	0.01	0.00	7.4	7.2	-3%
B2A4	90	2.03	1.75	19.3	18.2	-6%	88	0.01	0.00	7.6	8.0	6%
B2A5	90	2.03	1.75	17.3	20.2	17%	88	0.01	0.00	6.9	7.2	4%
B2A6	90	2.03	1.75	67.7	61.8	-9%	88	0.01	0.00	17.4	17.9	3%
B2 total				28.6	27.2	-5%				9.8	10.1	2%
B2 “n-1” total						-10%						1%
B2A2c	90	2.03	1.75	16.4	5.6	-66%	88	0.01	0	12.2	9.8	-19%
B2A3c	90	2.03	1.75	2.9	4.1	40%	88	0.01	0	5.4	8.1	49%
B2A4c	90	2.03	1.75	6.2	6.2	0%	88	0.01	0	9.2	7.8	-15%
B2A5c	90	2.03	1.75	9.7	10.5	9%	88	0.01	0	5.4	5.5	1%
B2A6c	90	2.03	1.75	26.4	29.9	13%	88	0.01	0	6.5	5.4	-18%
B2A7c	90	2.03	1.75	5.3	8.5	61%						
B2A9c	90	2.03	1.75	28.1	28.4	1%	88	0.01	0	10.2	10.8	7%
B2c total				13.6	13.3	-2%				8.2	7.9	-3%
B2c “n-1” total						21%						-9%

Table A3.9: Summer gas and winter electricity use in B3.

Energy type	gas	gas	gas	gas	gas	gas	elec	elec	elec	elec	elec	elec
Season	**sum**	**sum**	**sum**	**sum**	**sum**	**sum**	**win**	**win**	**win**	**win**	**win**	**win**
Period		**Pre**	**Post**	**Pre**	**Post**	**post-Pre**		**Pre**	**Post**	**pre**	**pre**	**post-Pre**
Parameter	**days**	**HDD/d (°C)**	**HDD/d (°C)**	**kWh/d**	**kWh/d**	**change**	**days**	**CDD/d (°C)**	**CDD/d (°C)**	**kwh/d**	**kwh/d**	**change**
B3A1*	121	0.03	0.01	13.8	14.9	9%	121	0	0.09	4.6	4.9	9%
B3A2	121	0.03	0.01	16.1	12.0	-25%	121	0	0.07	7.0	5.8	-17%
B3A3	121	0.03	0.01	12.6	12.9	2%	62	0	0.14			
B3A4	121	0.03	0.01	19.6	16.7	-15%	121	0	0.07	10.0	10.0	1%
B3A5	121	0.03	0.01	36.9	32.2	-13%	121	0	0.07	11.6	20.8	79%
B3A6	121	0.03	0.01	19.3	19.3	0%	121	0	0.07	10.5	10.9	4%
B3 total				19.7	18.0	-9%				8.7	10.5	20%
B3 “n-1” total						-3%						-1%
B3A1c	121	0.03	0.01	12.0	17.0	41%	121	0	0.09	41.8	13.0	-69%
B3A2c	121	0.03	0.01	24.3	21.4	-12%	121	0	0.07	10.9	11.5	5%
B3A3c	121	0.03	0.01	14.7	14.4	-2%	121	0	0.07	8.7	10.3	19%
B3A4c	121	0.03	0.01	11.1	11.7	5%	121	0	0.07	10.6	10.2	-3%
B3A8c	121	0.03	0.01	20.2	18.8	-7%	121	0	0.07	11.4	10.9	-4%
B3A9c	121	0.03	0.01	12.0	10.0	-17%	121	0	0.07	8.7	9.14	6%
B3c total				15.7	15.5	-1%				15.3	10.8	-29%
B3c “n-1” total						-7%						5%

Figure A3.1: Plots of annual pre- and post-retrofit energy use in study apartments and control apartments.

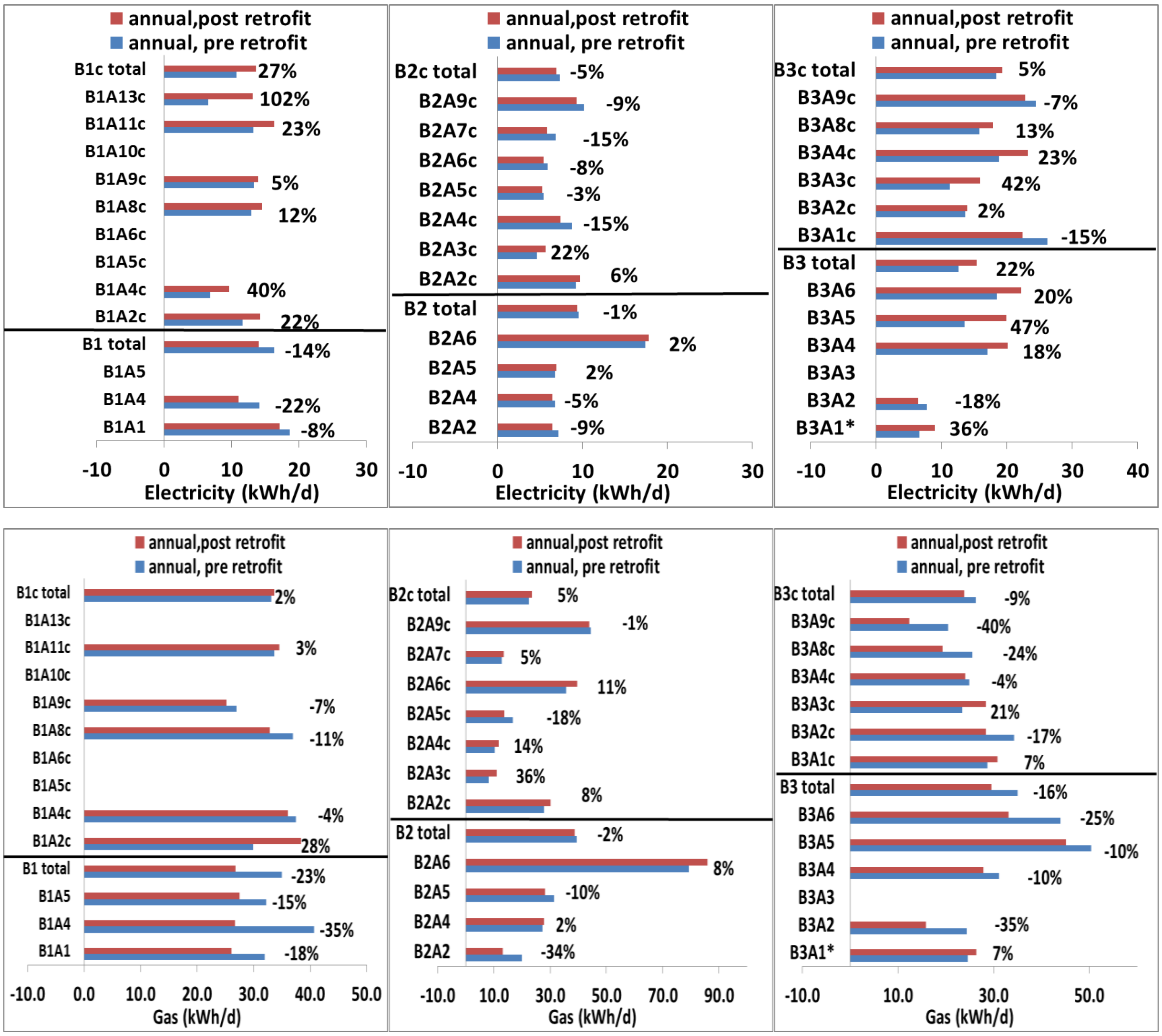

Figure A3.2: Plots of winter pre- and post-retrofit gas use and summer pre- and post-retrofit electricity use in study apartments and control apartments.

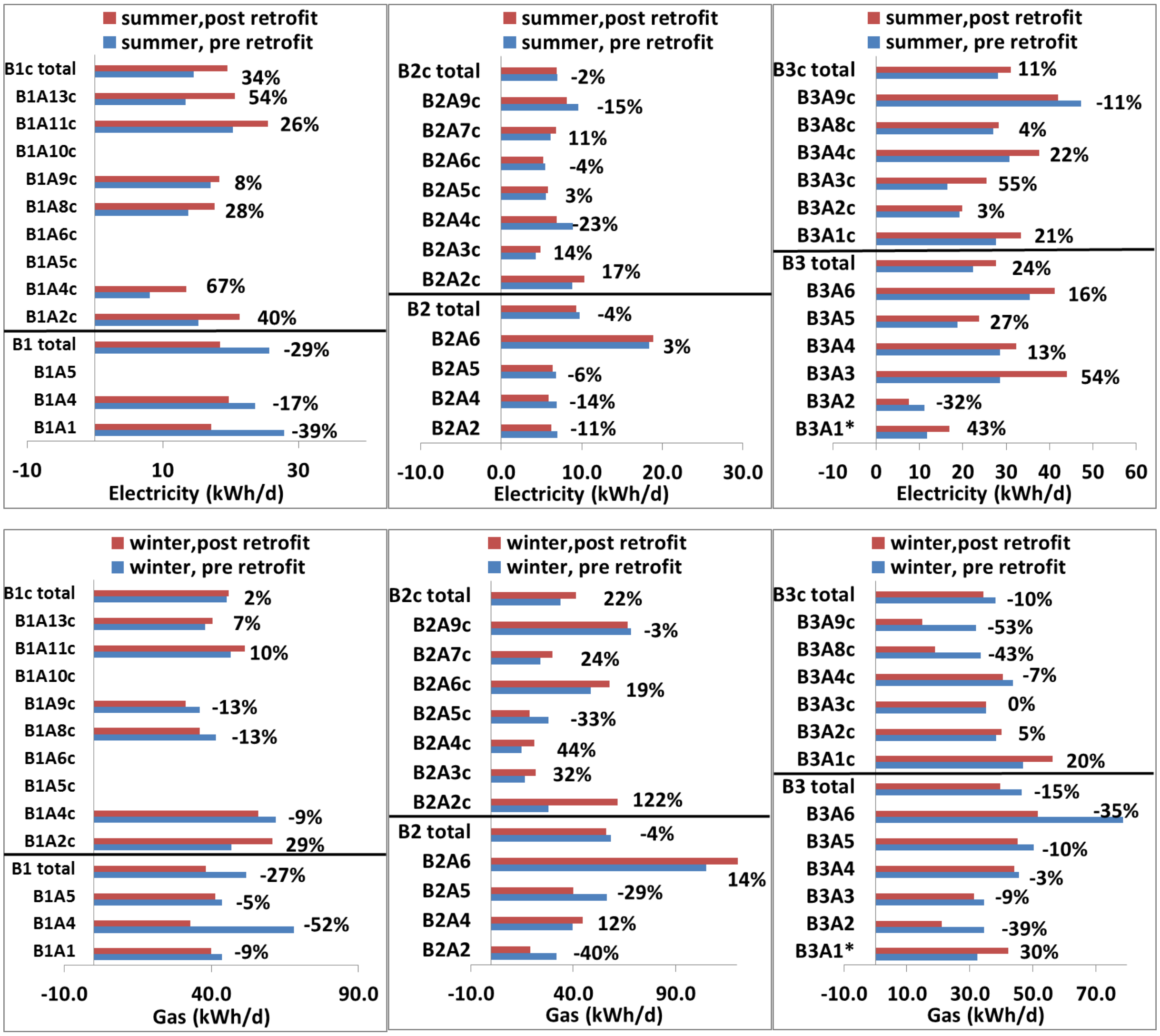

Figure A3.3: Plots of summer pre- and post-retrofit gas use and winter pre- and post-retrofit electricity use in study apartments and control apartments.